

Electrical Actuation

Technology Bridging

Final Report

Volume II

Final Report

NAS8-38609 D.O. 54

September 29-October 1, 1992
Huntsville, Alabama

**Proceeding of a workshop sponsored by
NASA Office of Space Systems Development
George C. Marshall Space Flight Center**



Baseline ELA Requirements for NLS and SRB

<u>Requirement</u>	<u>NLS TVC Regmts.</u>	<u>SRB TVC Regmts.</u>
Peak Power:	59 kW	83 kW
Base Power	5.7 kW	6.8 k
Average Power	8.2 kW	33.1 kW
Voltage	200 Vdc	200 Vdc
Pulse Duration	.5 sec.	1.5 sec.
Pulse Frequency	10 sec.	4.25 sec.
Energy / Pulse	7.4 Wh	32 Wh
Max. No. of Pulses	54	29
Operating Time	9.5	2.1
Total Energy	1.3 kWh	1.16 kWh

contin.



ELA System Power Source Alternatives

- A variety of ELA systems and requisite power source combinations are being considered for many different applications (launch vehicle TVC, PCV, Orbiter flight control, steering, braking, GSE fluid control, planetary surface equipment)
- Each ELA and system application means unique power characteristics to maximize system operation and efficiency, while minimizing costs
- ELA power source alternatives include:
 - high power density batteries
 - advanced fuel cells
 - gHz turbine-driven alternators
 - flywheel energy storage devices
- Each power source type is viable and appropriate for a specific ELA application and set of program/vehicle constraints



ELAPSS Purpose & Scope

- The ELA Technology Bridging Programs integrated ELA & power systems test & demonstration plans require power output capability which characterizes all power source options for the variety of ELA applications
- Acquisition or development of actual power source devices is not practical within ELA-TB Program budget and schedule constraints
- The ELAPSS will provide a programmable power source emulation capability to meet all NASA ELA application/system test & demonstration needs
- One ELAPSS can be developed to emulate the defined operating characteristics of any power source using commercially available hardware and applications software

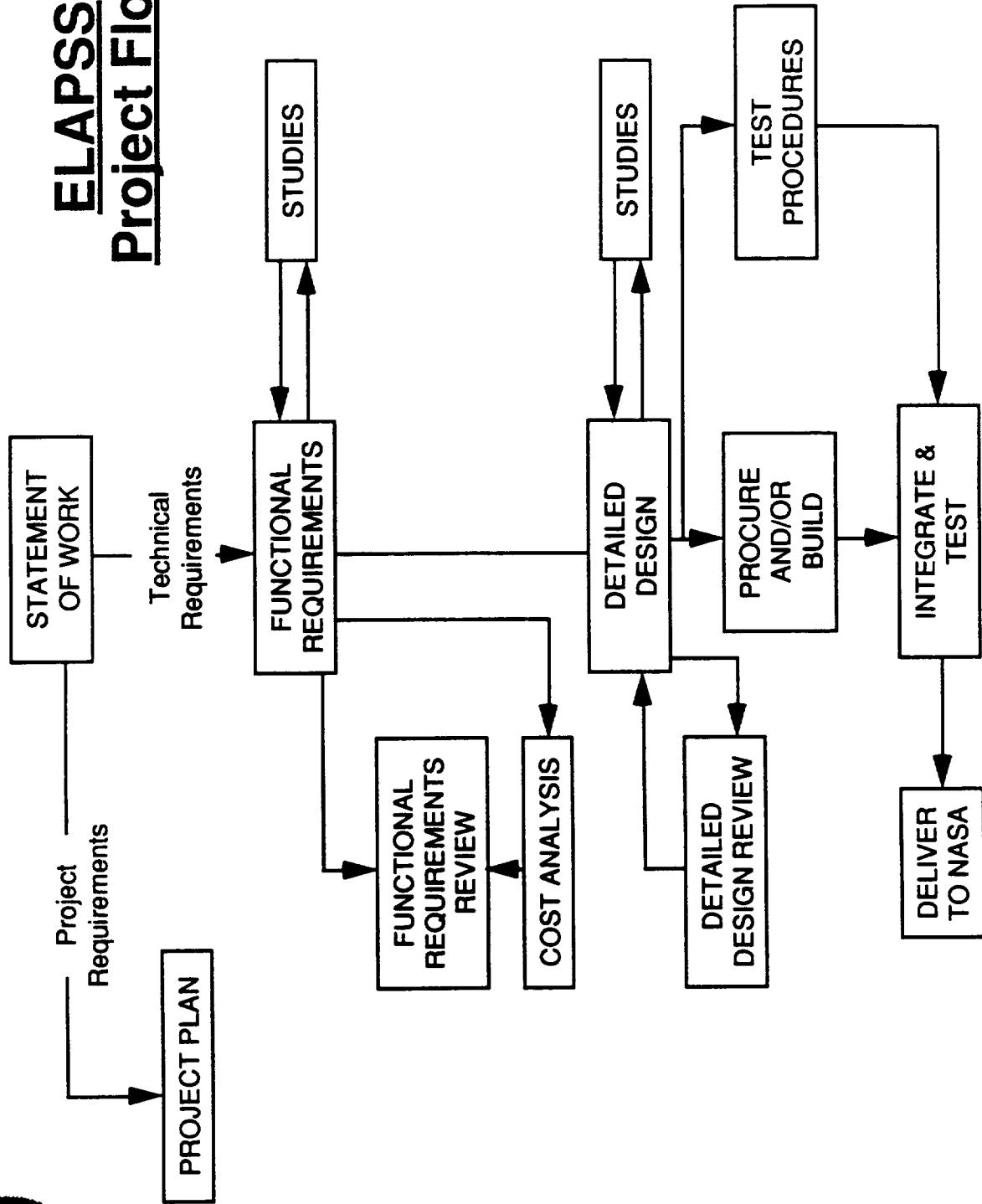


ELAPSS Purpose & Scope (cont'd.)

- A modular design will allow the ELAPSS to be reconfigured to support multiple ELA system sizes, redundancy schemes, and integrated ELA/power system performance and fault testing
- The ELAPSS will provide a permanent power source simulator capability for use on current and future NASA programs
- The ELAPSS will be a portable piece of NASA GSE for use at any NASA center with the facility to support it
- The ELAPSS will be developed with commercial components for more timely development & use, more cost effective replication, and future expansion of power source emulation capability
- The ELAPSS allows very robust power degradation and fault testing capability via automated test sequences or manual commands from an operator control console



ELAPSS Project Flow



ELAPSS Development Approach



Industry ELA
Power Reqmts.

ELA-TB Power
Reqmts. Def.

ELAPSS
Systems
Requirements

Battery Reqmts.
Analysis

Fuel Cell Reqmts.
Analysis

Alternator/Flywheel
Reqmts. Analysis

ELAPSS System
Design Concept

ELAPSS Design/
Cost Trades

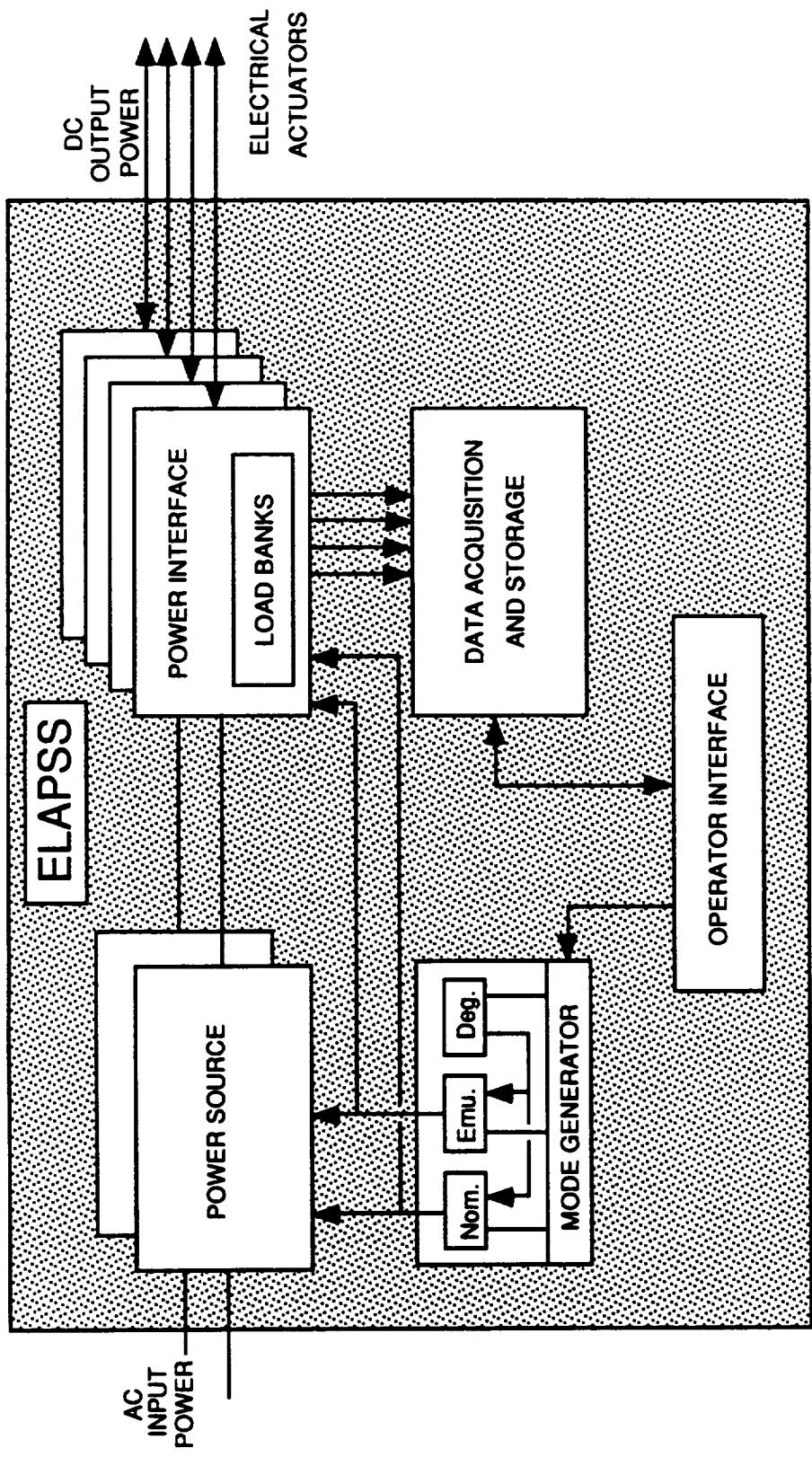
ELA
Technology
Bridging
Program
Coordination,
ELAPSS
Reviews,
& Direction

ELAPSS
Project Technical
Coordination &
Integration

- Review by Committee
- Task Agreements via EMs

Iterate ELAPSS Reqmts. & Design

ELAPSS Functional Diagram



ELAPSS FUNCTIONAL BLOCK DIAGRAM

ELA Technology Bridging Program Power Source Simulator

Electrical Actuation Power Source Simulator (ELAPSS)

REQUIREMENTS

- * ELAPSS will provide power for a variety of non-flight Electrical Actuators - up to 120 kW at 28, 120, 200 and 270 Vdc.
- * ELAPSS will be able to provide nominal power or emulate Batteries, Fuel Cells, Turbo Alternators and Flywheels
- * ELAPSS will be able to provide off-nominal power in either nominal or emulation power modes. Off-nominal power could be EMI injection, power source faults and line faults.
- * ELAPSS will be able to absorb returned energy from the ELA
- * ELAPSS will be able to support redundant ELA testing



BASIC DESIGN CONCEPT

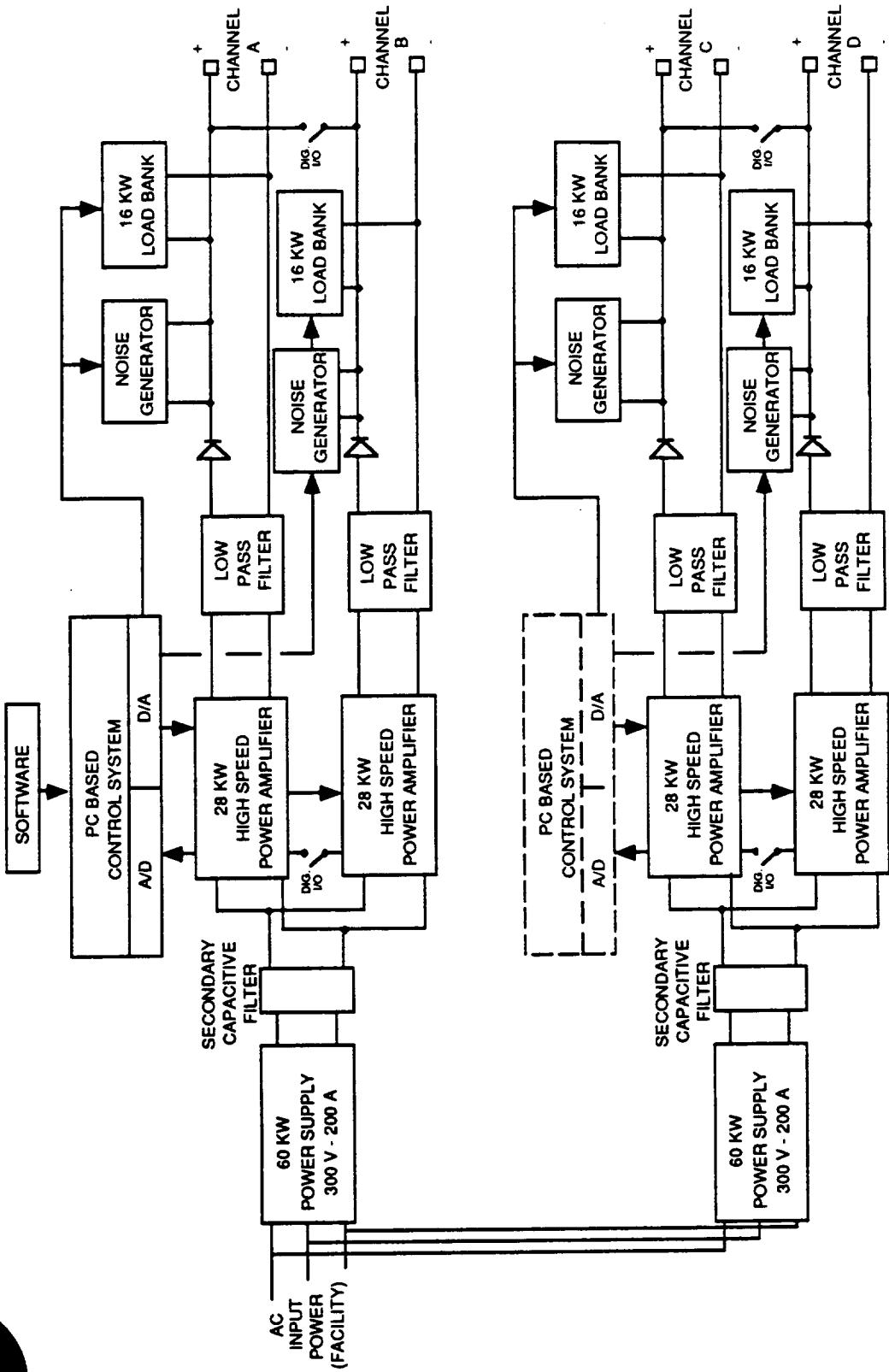
The proposed Electrical Actuator Power Source Simulator will have following basic components:

- A programmable switch-mode DC Power Supply
- PWM Power Amplifiers
- A microcomputer based instrumentation and control system





JSC Navigation, Control & Aeronautics Division



ELAPSS FOUR CHANNEL HARDWARE CONFIGURATION



DC POWER SUPPLY:

The DC Power Supply provides variable dc power for the power amplifiers from the utility power. To insure that the system output will respond as fast as the amplifiers are capable, it has a large capacitor bank at the output terminal. The DC power supply is separate module in the ELAPSS system and hence, can be reconfigured easily.

PWM POWER AMPLIFIERS:

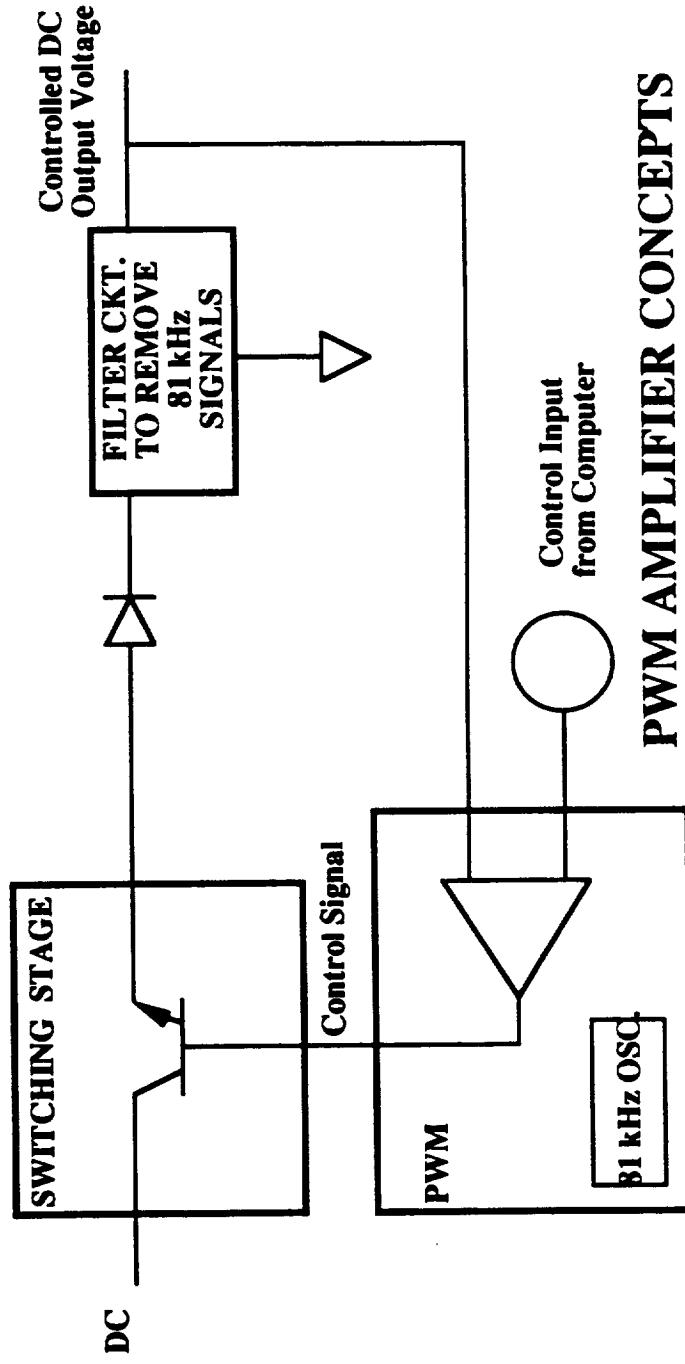
These are high power Pulse Width Modulated switching amplifiers that can be designed as master-slave system to allow paralleling multiple modules to meet high power need. Each amplifier contains power modules consisting of a full H-bridge switching stage. The input to the power module is a 81 kHz control signal. The output of each power module is a series of power current pulses at 81 kHz rate whose width is proportional to the analog control signal.



PWM POWER AMPLIFIERS (Contd.):

The PWM output is then applied to a low pass filter to eliminate the 81 kHz and its harmonics. The resultant output is DC with little ripple content.

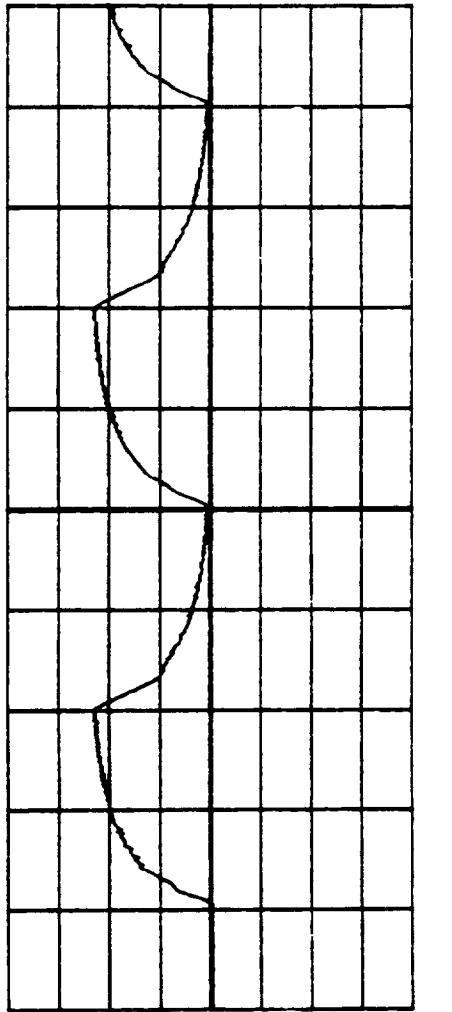
The PWM switchmode type of amplifiers is important for this design because it allows a large output voltage range without dissipating excessive amounts of heat.



PWM AMPLIFIER CONCEPTS

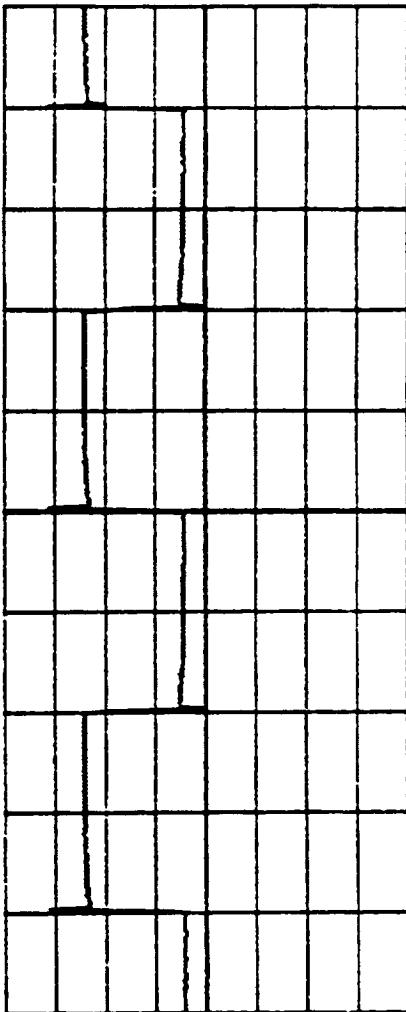
JSC Navigation, Control & Aeronautics Division

**Power Simulator (without PWM Amp) Output
Transient Response with Step Control Input**



.5 sec/div

**Power Simulator (with PWM Amp) Output
Transient Response with Step Control Input**



.5 sec/div

ELA Technology Bridging Program Power Source Simulator

September '92 Review





MICROPROCESSOR CONTROLLER:

This consists of an industrial PC and instrumentation and control modules. The system load current is monitored by current sensor and processed by an analog to digital converter (ADC). The data read from the ADC module is used by the microprocessor to calculate the voltage control signal for proper simulation output. This control signal is then sent to the power amplifiers via a digital-to-analog converter.



OFF-NOMINAL OPERATION

IN ADDITION TO THE BASIC SYSTEM COMPONENTS, THE FOLLOWING MODULES ARE REQUIRED FOR DEGRADED OR OFF-NOMINAL MODE OF OPERATION:

- **NOISE GENERATOR:**
A signal generator and wide band amplifiers may be used to inject noise into the output line to degrade output power.
- **LOAD BANKS:**
These are active control MOSFET off the shelf modules which act as current sinks to absorb return energy from the ELA under test. These devices are turned on by the micro-computer controller.

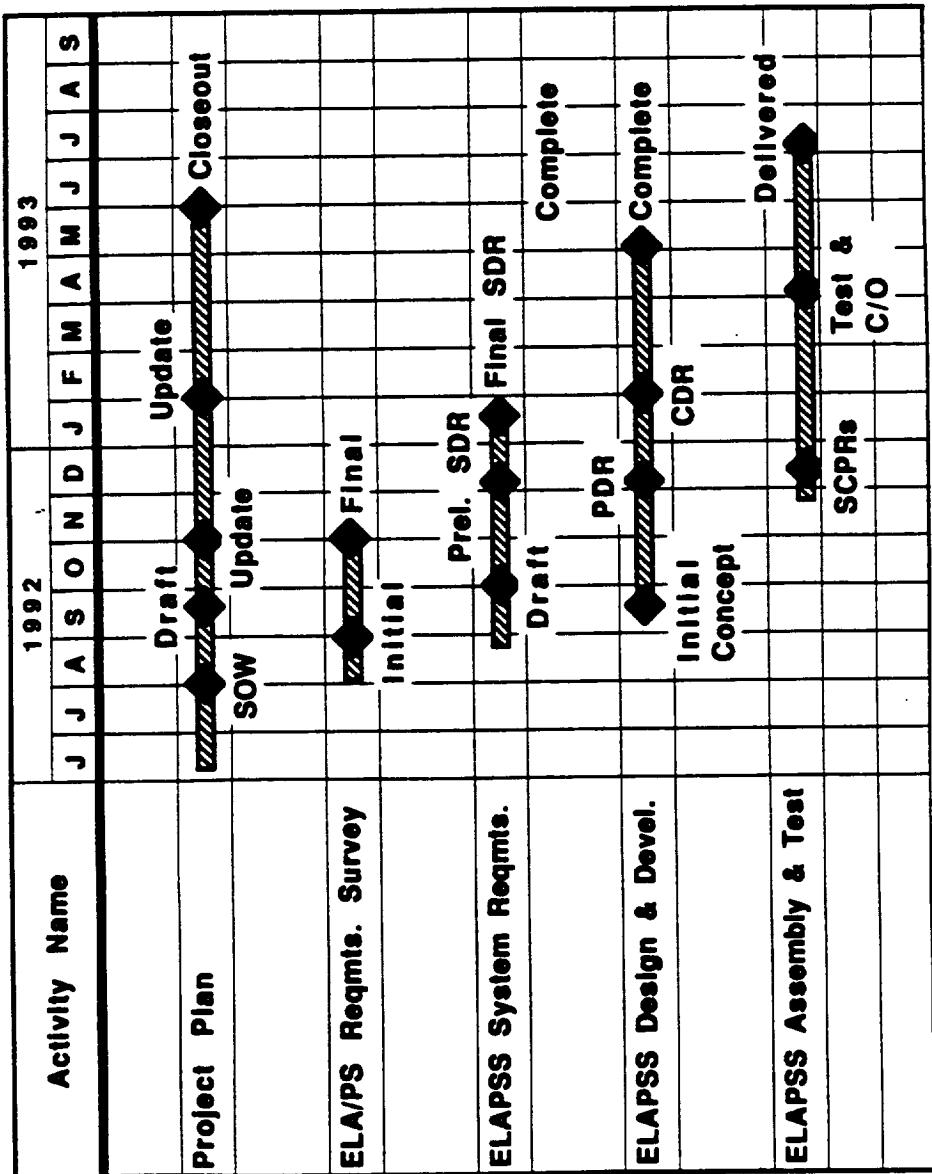
Both the noise generator and the load banks are commercially available modules.



ELAPSS Design Drivers

- High power output capability:
 - 60 - 90 kW TVC requirements for NLS, ASRM (SRB)
 - 90 kW peak power required to meet SRB TVC ELA reqmts.
(SRB start transient and roll maneuver load profiles)
- Dual & Quad redundant ELA system test capability
 - NASA-MSFC building a quad 60 kW system (4 - 15 kW motors)
 - NASA-LeRC building dual 60 & 80 kW systems
- EMI characteristics of the power bus with switching loads
- Return energy absorption capability (from each channel)
- ELA power transients (engine start, roll maneuver) exceed the response time of fastest programmable power supply available

ELAPSS Project Schedule (FY'92)





ELAPSS Value To NASA

- Supports verification of any NASA ELA systems performance & fault tolerance/redundancy with appropriate representative power source emulation
- A programmable portable ELAPSS capability supports multiple ELA applications testing at any NASA site with supporting facility
- ELAPSS provides a permanent resource to NASA - a link in the chain of end-to-end integrated power/avionics advanced development and test capability for any vehicle/surface system
- Modular, commercial ELAPSS design provides multiple ELA/power system testing flexibility, and allows easy reconfiguration, expansion or replication as required
- Supports the NASA "bridging" concept - new way of doing business
 - resource sharing among centers & programs

ELA OPERATIONS

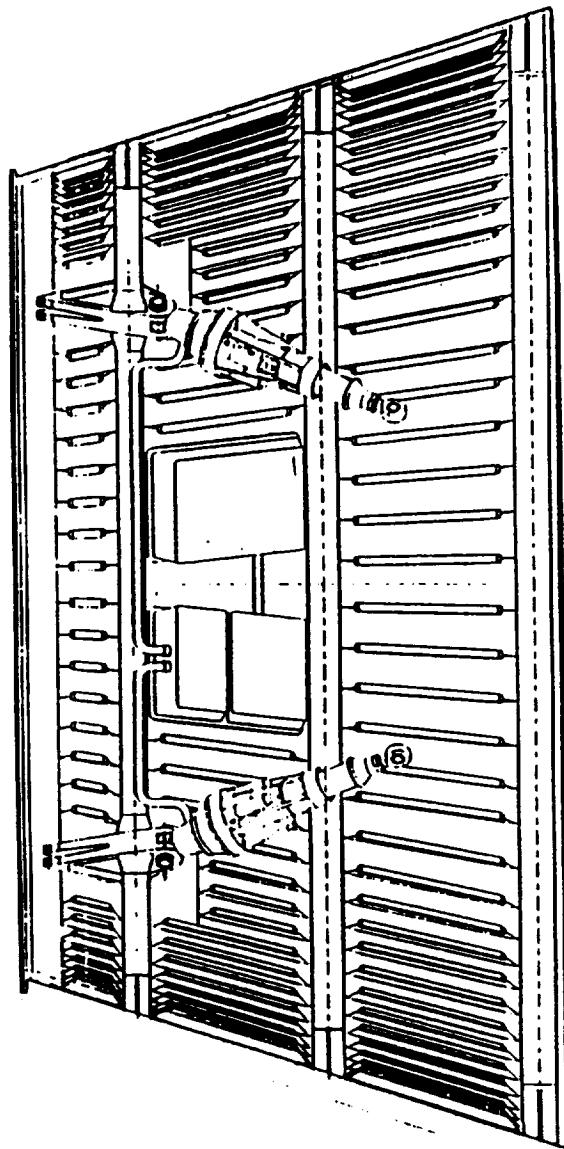
SESSION VII

September 29, 1992

ELECTRIC ACTUATION

TECHNOLOGY BRIDGING PROJECT WORKSHOP

STS HYDRAULIC VS. ELA OPERATIONS SRB ASSESSMENT



(ELECTRIC SRB AFT SKIRT CONCEPT)

Carey M. McCleskey, NASA/KSC
Haley W. Rushing, ASSI/KSC

WHY AN ELA OPERATIONS TEST BED?

IF A **CONCURRENT ENGINEERING** APPROACH TO DESIGN IS TO BE USED, THE LAUNCH SITE OPERATIONS CUSTOMERS WILL NEED TO GAIN **KNOWLEDGE, SKILLS AND ABILITIES** IN THE FOLLOWING AREAS:

1. SKILL IN HANDLING HIGH POWER BUSSES

- SIGNAL MEASUREMENT BETWEEN LRU'S
- GSE REQUIREMENTS & CHARACTERISTICS
- SWITCHING AND BUS REDUNDANCY/ISOLATION CHARACTERISTICS

2. KNOWLEDGE OF POWER SOURCE CHARACTERISTICS

- BATTERY HANDLING AND MAINTENANCE
- FLYWHEEL OPERATION

3. ABILITY TO HANDLE PERSONNEL SAFETY ISSUES

- BATTERIES
- HIGH VOLTAGE LINES

4. KNOWLEDGE OF ACTUATOR OPERATION

- LOCKING OPERATION AND CHARACTERISTICS
- ACTUATOR INITIALIZATION
- GENERAL OPERATING CHARACTERISTICS
(CURRENT MONITORING / TORQUE EQUALIZATION / VELOCITY SUMMING)

5. EXPERIENCE IN SYSTEM-LEVEL ISSUES

- DATA MANAGEMENT
- FAULT MANAGEMENT
- ENERGY MANAGEMENT (CHARGE/DISCHARGE CYCLES)



Agenda

- ♦ *Motivation*
- ♦ *SRB TVC Ops Study Results & Video*
- ♦ *Future Plans*



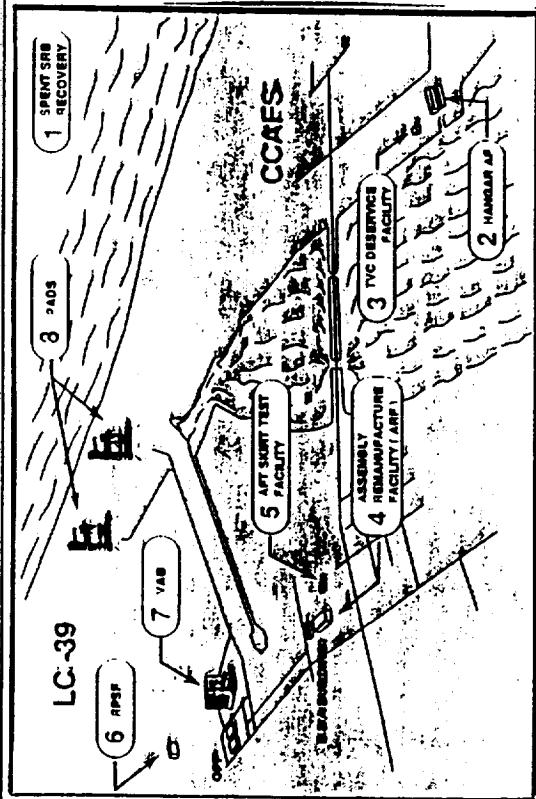
Motivation

- *Operational experience with Shuttle*
- **Heavy servicing and deservicing requirements**
- **Replacement often difficult**
- **Heavy infrastructure overhead**
 - Facility
 - Ground Support Equipment
 - Toxic Commodities
- **Objective**
 - *Identify Life Cycle Cost of Current Technology*
 - *Conduct specific one-for-one trades with electric actuation technology Life Cycle Cost opportunities*
- **Flight Control Candidates for study:**
 - *Orbiter (APU/Hyd - Aero/TVC/Prop/Ldg-Decel)*
 - *SRB Thrust Vector Control System*

HYDRAULIC VS ELECTRIC LIFE CYCLE SUMMARY

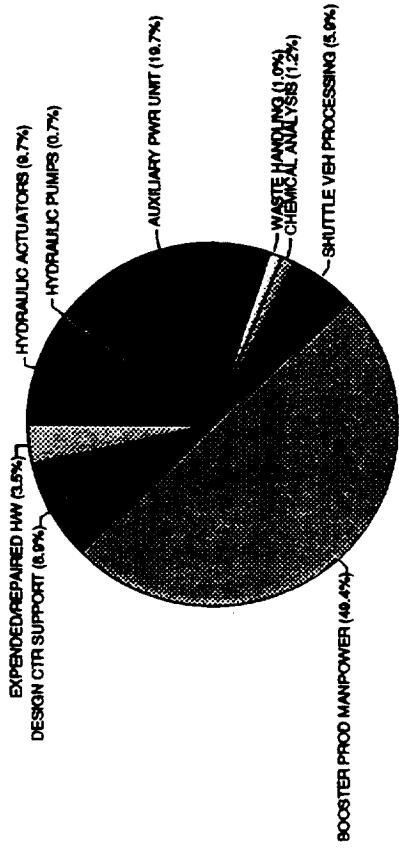
- REFURBISHMENT COSTS APPROX 2/3 REDUCTION
- REFURBISHMENT/CHECKOUT TIME 3/4 REDUCTION
- 8400 SQ FT REDUCTION IN FACILITY REQUIREMENTS (+ CLEAN ROOM + FLUID SERVICES)
- HUNDREDS AND HUNDREDS OF GSE ITEMS ELIMINATED - VERY FEW INTRODUCED

SRB TVC WORK FLOW/SEQUENCE



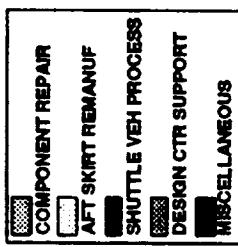
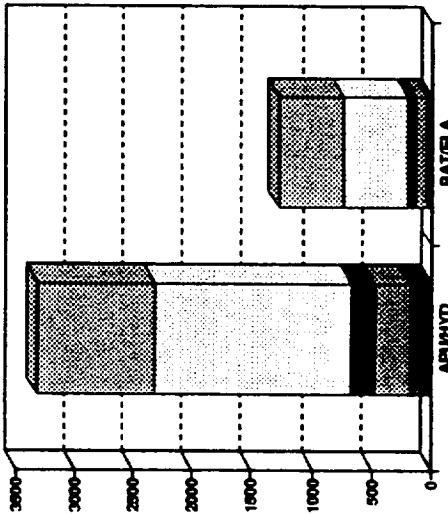
SRB TVC LIFE CYCLE COST ELEMENTS

(System Costs = \$ 3.3M Per Flight)



SRB TVC HYD VS. ELA (INTERIM RESULTS)

(Cost Savings = \$ 2.0M Per Flight)



CONFIRMATION STUDY
ON ELA COST SAVINGS
APPROVED FOR FY 1992



Future Plans

- Continue updating SRB TVC Life Cycle Costs

- Support New Launch System studies

- Begin identifying Orbiter costs in greater detail

Establish capability to support operational demonstrations for the investigation of:

- Safety
- Ground support equipment (GSE)
- Facility requirements
- Operability investigations:
 - Installation
 - Replacement
 - Test and problem isolation
 - Servicing & maintenance
 - Processing flow analysis & resource usage
 - Launch commit criteria and hold impact

NASA Electrical Actuation

Technology Bridging Workshop

ELA Ground Support Applications

at the

John C. Stennis Space Center

W. W. St. Cyr

Technology Development Division
Science & Technology Laboratory

POTENTIAL ELA GROUND APPLICATIONS AT SSC

- Variable position valve of NASP High Heat Flux Test Facility
- Automation of High Pressure Gas Facility
- CTF Test Cell
- Seal Configuration Tester
- Selected Facility Support System Valves

GOALS OF ELA PROGRAM AT SSC

- Determine significant advantages and disadvantages of using ELA's for facility valve actuation.
- Compare operating characteristics of ELA's to those of hydraulic control valves.
- Establish reliability of commercially available ELA hardware when used on facility control valves.
- Determine the compatibility of ELA control interfaces with existing facility data acquisition and control systems.

PROGRESS TO DATE / PROGRAM STATUS

- Requirements have been established for specific applications.
- Identified commercial hardware for ground support applications.
- Developed test plan.
- Electrical Actuator (commercial hardware) in Procurement.
- Adapting test plan to commercial hardware.
- Commercial hardware to be evaluated:
- ELA hardware to be tested Oct/Nov on Seal Configuration Tester,
- Field application and evaluation of ELA during 2nd, 3rd and 4th quarter of FY93.

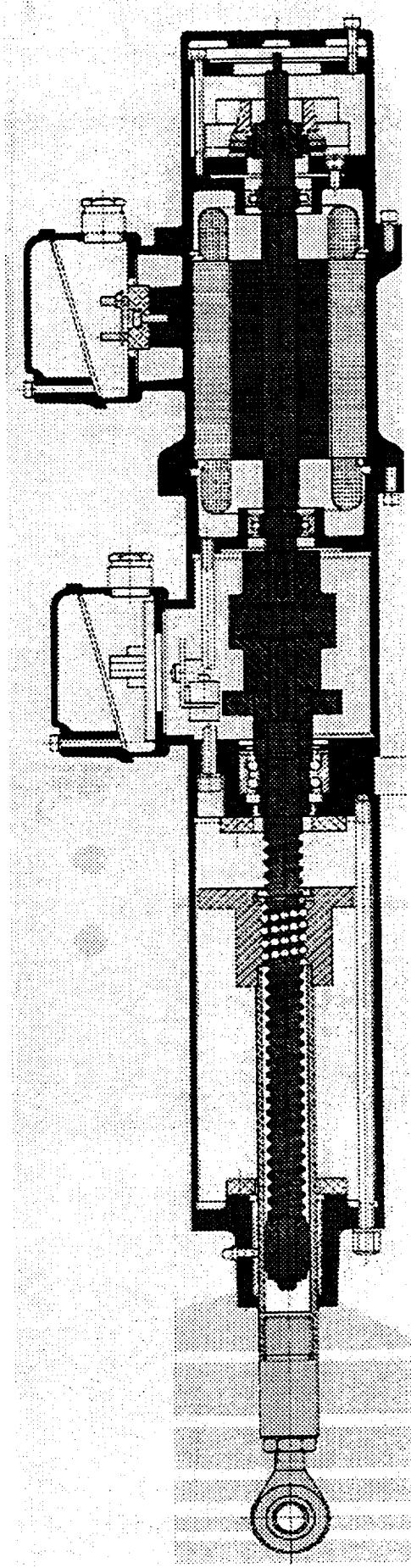
STENNIS SPACE CENTER ELECTRICAL ACTUATOR ASSESSMENT



Stennis Space Center



INTERNATIONAL



ELA SPECIFICATIONS

Manufacturer:	Raco International, Bethel Park, PA
Stroke:	7.9"
Thrust:	5000 lbs
Rod Speed:	6 ips peak running (5.5 Hz max)
Lead:	12 mm Ball Screw
Motor:	Brushless Digital Servo Direct Drive, 1550 RPM
Mounting:	Front Flange & Trunnion Brackets
Length:	Approx. 6'
Accessories:	Power Release Brake, Spring loaded front clevis, Stroke limit switches, Rotary encoder for linear displacement

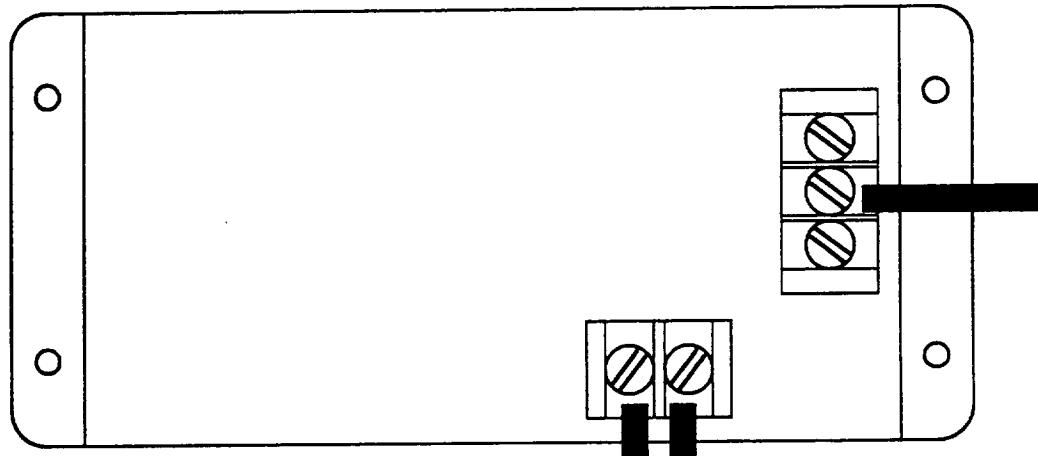
ELA SERVO MOTOR HIGHLIGHTS

- 3 Phase Brushless Servo Motor
- Position Repeatability: Better than one arc-minute
- Maximum Speed: 1550 RPM
- Continuous Torque: 80 lb.ft.
- Rotor Inertia: $0.00093 \text{ lb.ft.sec}^2$
- Load Inertia Range: 0 to $0.0465 \text{ lb.ft.sec}^2$

ELA CONTROLLER HIGHLIGHTS

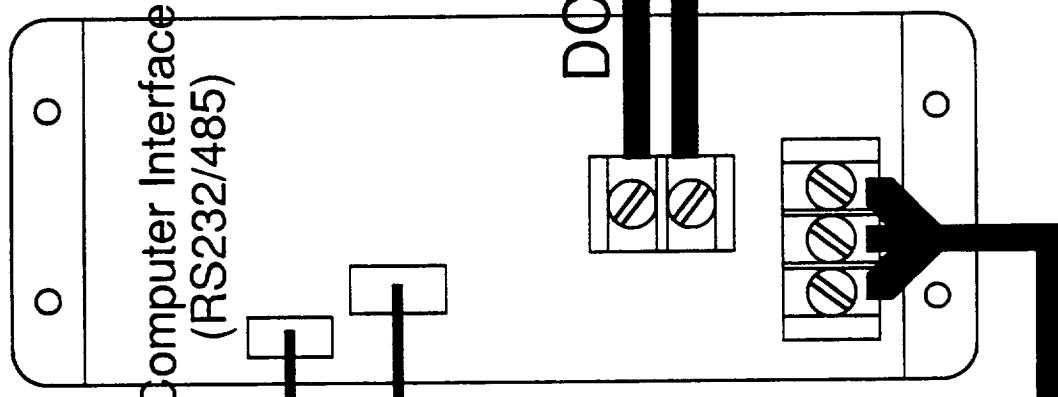
- 10 kHz PMW Switching Frequency
- 55 Amp/Phase Continuous Current
- 110 Amp/Phase Peak Current
- 230 V RMS Nominal Voltage

Power Supply



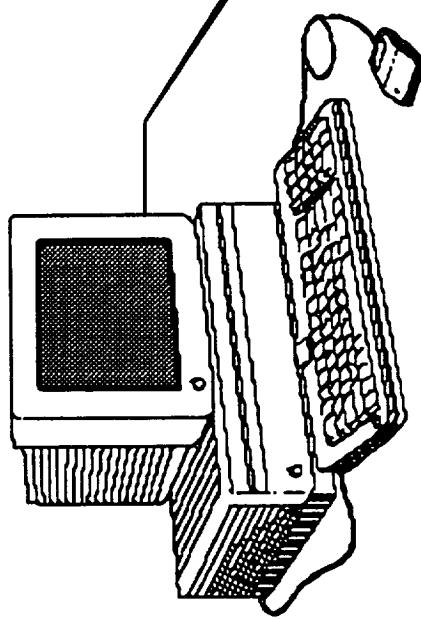
230 VAC 3Φ

Controller



DC Bus

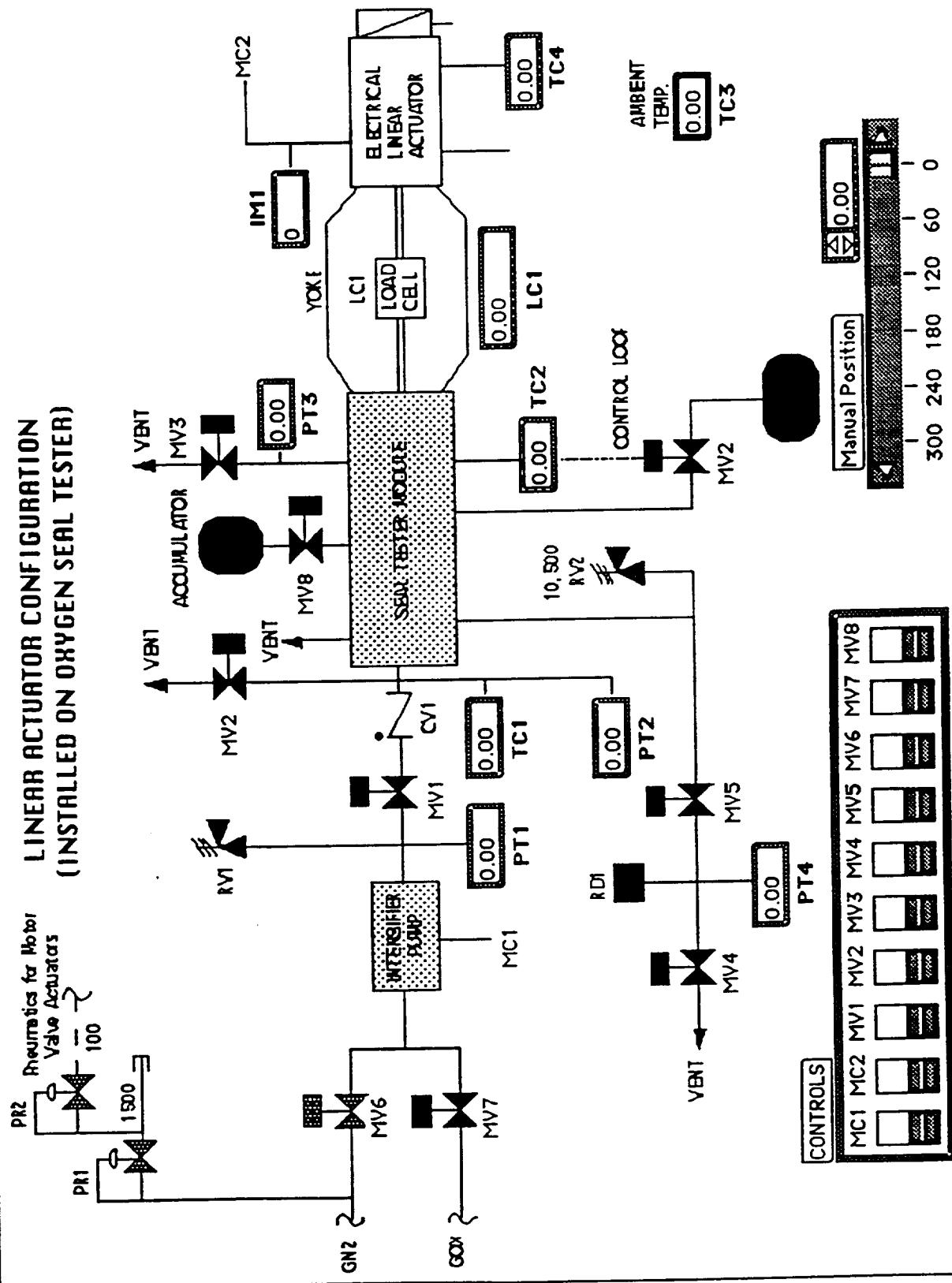
**Computer Interface
(RS232/485)**



Servo Motor

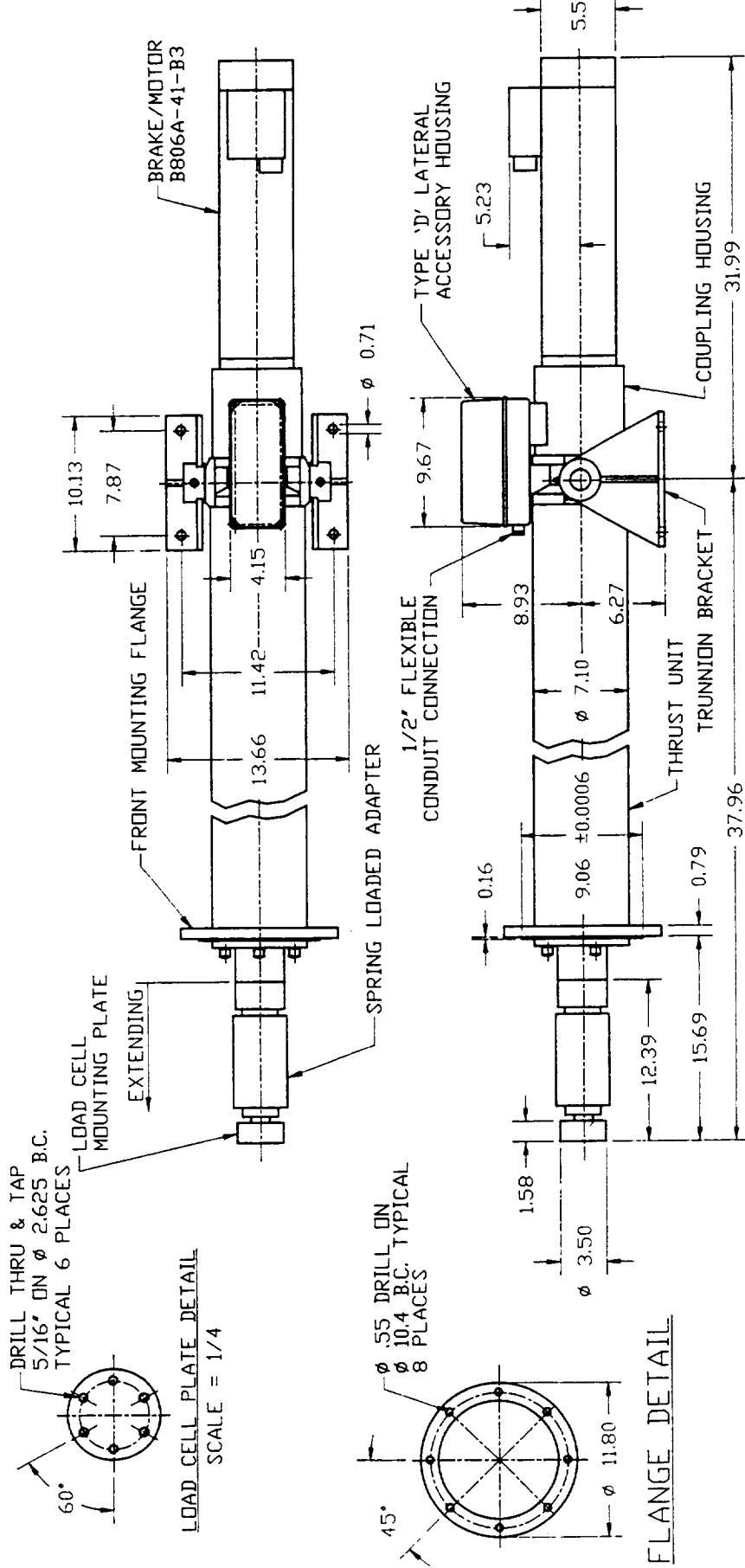
ELECTRICAL ACTUATOR TESTBED

LABVIEW CONTROL PANEL

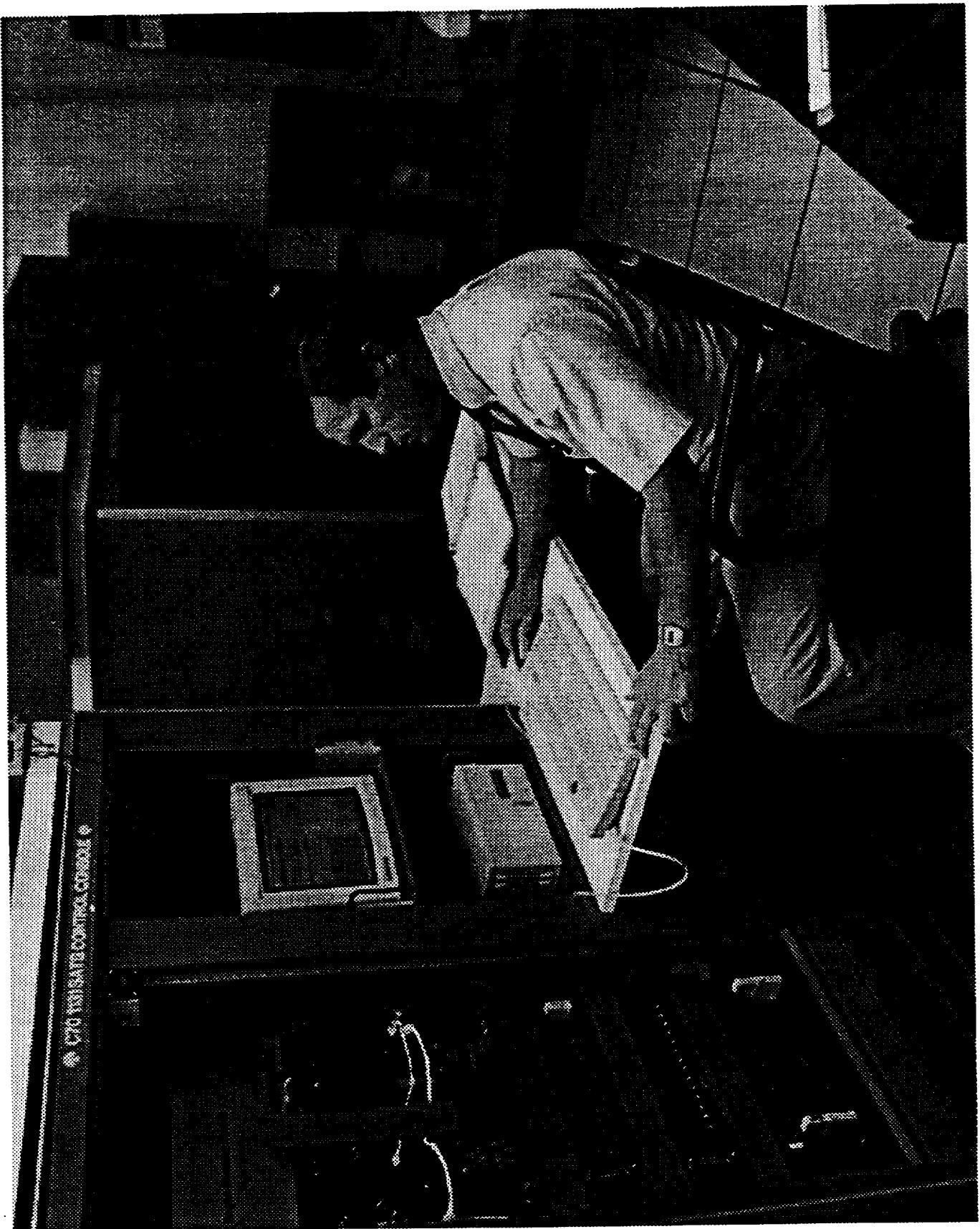


ELA TESTBED MEASUREMENTS

- Load (10 kHz sampling)
- Linear Position (10 kHz sampling)
- Linear speed and acceleration (derived from position)
- Motor current draw
- Motor temperature
- Total run time
- Wear characteristics of critical ELA drive components



RACO INTERNATIONAL, INC.	RACO
P.O. BOX 151	BETHEL PARK, PA 15102
TYPE F7 ACTUATOR WITH FRONT FLANGE AND	TYPE 'D' LATERAL ACCESSORY HOUSING
STROKE = 7.9"	STROKE = 7.9"
SCALE 1/8	DR. BY P. SPANO
DATE 6-4-92	CKD. BY P. SPANO



ELA CONTROLLER, POWER SUPPLY, AND OPERATOR CONSOLE

POWER-BY-WIRE FLIGHT DEMONSTRATIONS
ON LASC'S HTTB

ORIGINAL PAGE IS
OF POOR QUALITY

Lockheed
High Technology Test Bed
HTTB

ORIGINAL IMAGE IS
OF POOR QUALITY

LOCKHEED HILLS

High Technology Test Bed Program

/

Future Technologies



- Short Takeoff and Landing
- Fly by Wire
- Voice I/O
- Infrared
- High Pressure Hydraulics
- High Speed Data Bus
- Fiber Optics
- Eye-Safe Laser
- Autonomous Navigation
- Head-Up Display
- Digital Flight Control



LOCKHEED AIRBORNE DATA SYSTEM (LADS)

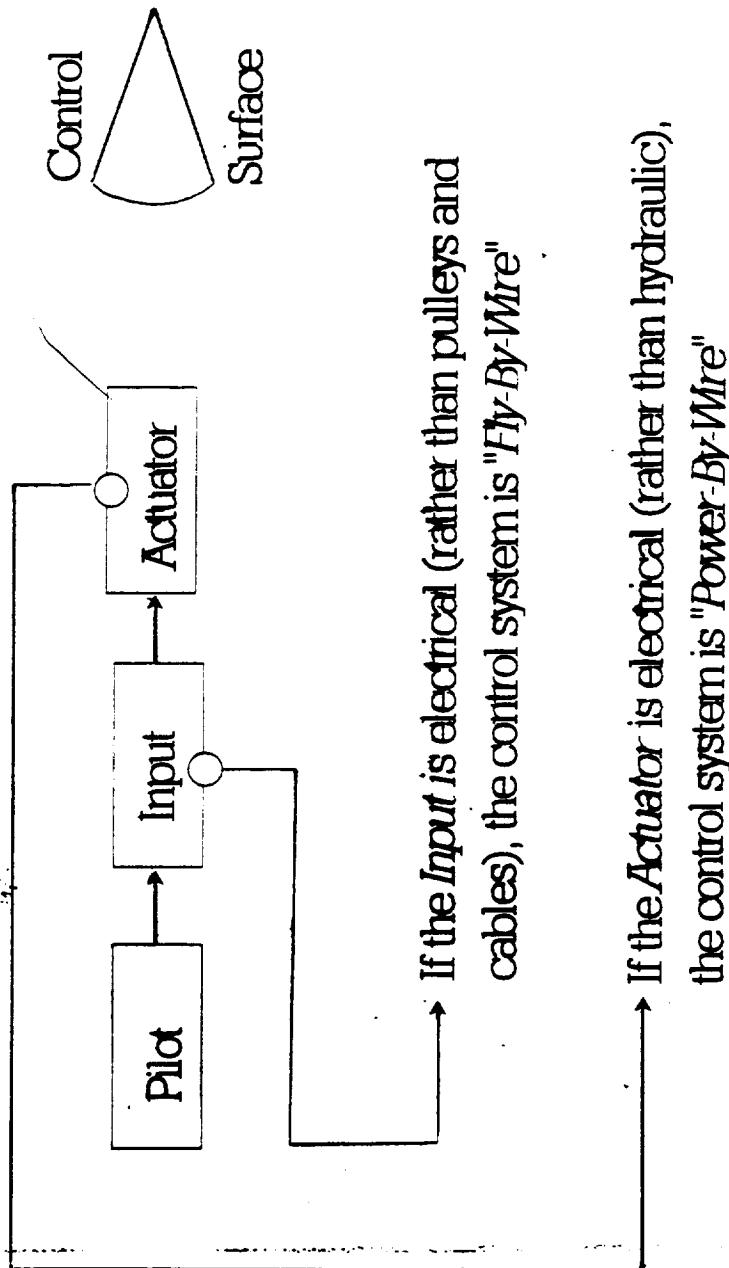
- Recording System Installed
- Multiple Measurements Available
- Modular/Expandable
- Real-Time Data
- Processed Output In Engineering Units
- Scan Rates to 160/sec



POWER-BY-WIRE

What is PBW?

Power-By-Wire is the use of electrically powered actuators (rather than hydraulic) in aircraft primary flight control systems



POWER-BYWIRE

What is PBW?

There are two general types of Power-By-Wire actuators-

- Mechanical Transmission - an electric motor/gear train linked mechanically to the control surface. A so-called Electro-Mechanical Actuator (EMA). These can have rotary or linear output.
- Fluid Transmission - a small, local hydraulic power system (electric motor driven pump and reservoir) powering a cylinder and piston assembly. Sometimes also called "Dispersed Hydraulics". There are two categories:

The Electro-Hydrostatic Actuator (EHA) - closed loop motor control.

The Integrated Actuator-Package (IAP) - closed loop pump control.

POWER-BY-WIRE

Why PBW?

Aircraft power generation for primary flight control is more efficiently accomplished electrically than it is hydraulically.

This leads to several areas where PBW can offer potential improvement:

- Reliability, Maintainability, and Life Cycle Cost - In our C 141 RAMTIP, we found that a fleet retrofit to PBW provides the equivalent of 3.5 to 6.5 additional aircraft based on R&M benefits.
- About a 2 times Reliability improvement MTBF.
- About a 4 times Maintainability improvement - due mainly to the reduction in troubleshooting time provided by automated diagnostics.

POWER-BY-WIRE



Lockheed Involvement:

LMSC - in 1982 Sundstrand developed prototype Electromechanical PBW systems for thrust vector control of a Trident upper stage.

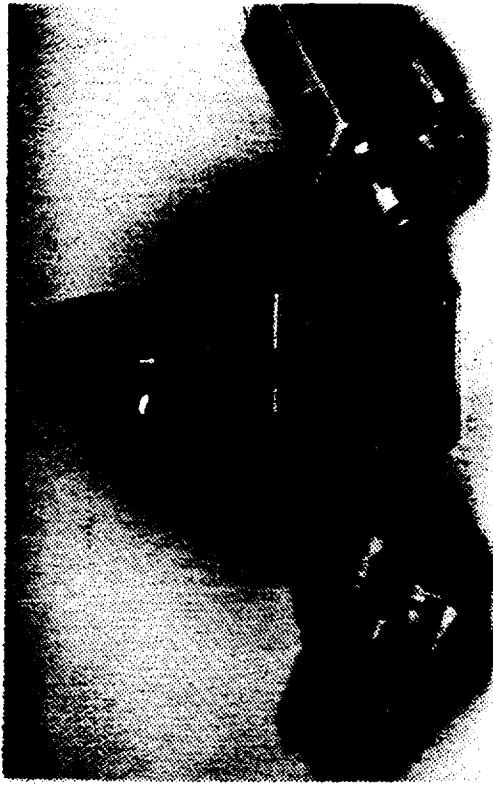
ADP - in 1987 at Rye Canyon - evaluated the Parker-Bertea Electrohydrostatic Actuator package developed for the Boeing 7J7.

LASC - has programs to flight test demonstrate PBW on two of our Aircraft:
the C141 and the HTTB.

POWER-BY-WIRE

Lockheed Involvement

ELECTROMECHANICAL ACTUATION



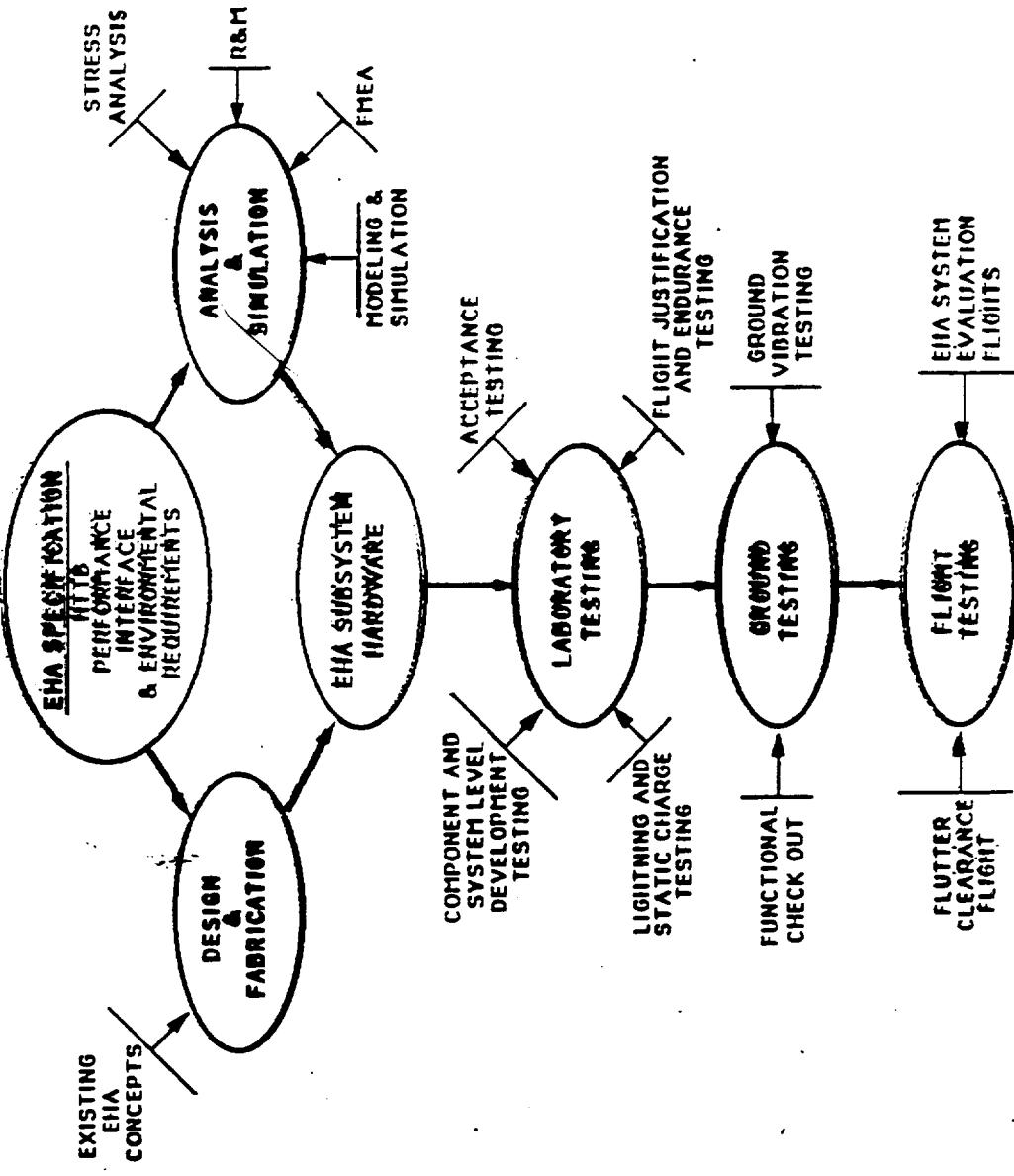
- Based on Systems Developed By Sundstrand for Boeing's CONDOR Autonomous Unmanned Vehicle (UAV)
- 3 Axes SCAS (Rotary) and 2 Axes Tabs (Linear): A total of 7 Actuation Systems
- Initial Flights in Early 1989: First Fully STOL Flight 13 July 1990
- Systems Are Flight Phase Critical

PROGRAM OVERVIEW

- FLIGHTWORTHY ELECTROHYDROSTATIC ACTUATION SUBS
 - Specified By LASC
 - Developed, Fabricated, & Lab Tested By The Control Systems Division Of Parker Beretta

- FLIGHT TESTING OF THE EHA IN THE HTTB
 - Conducted By LASC Out Of Dobbins AFB, Marietta, GA
 - Total Of Five Flights - Dec 91 Through Mar 92

EHA / HTTB PROGRAM APPROACH



POWER-BY-WIRE

Locidized Involvement

ELECTROHYDROSTATIC ACTUATION

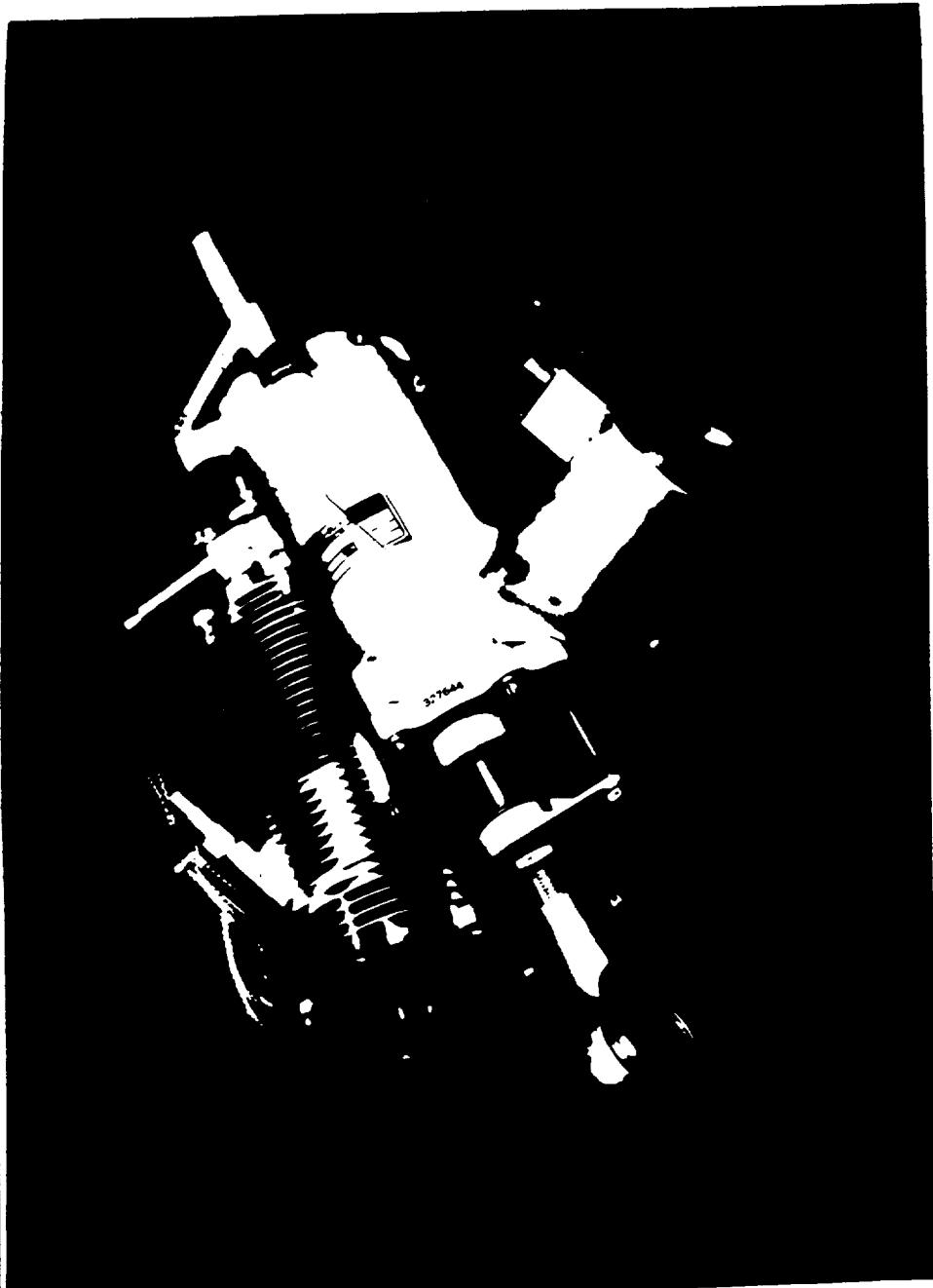


System Developed By Parker-Bertea for B7J7

- Flown on HTTB Aileron 6 Dec 1991 - Industry First Flight Test of an EHA
- Lab Endurance Tests of 90,000,000 Cycles
- Air Force CRAD Program Out of OCALC, \$0.6M

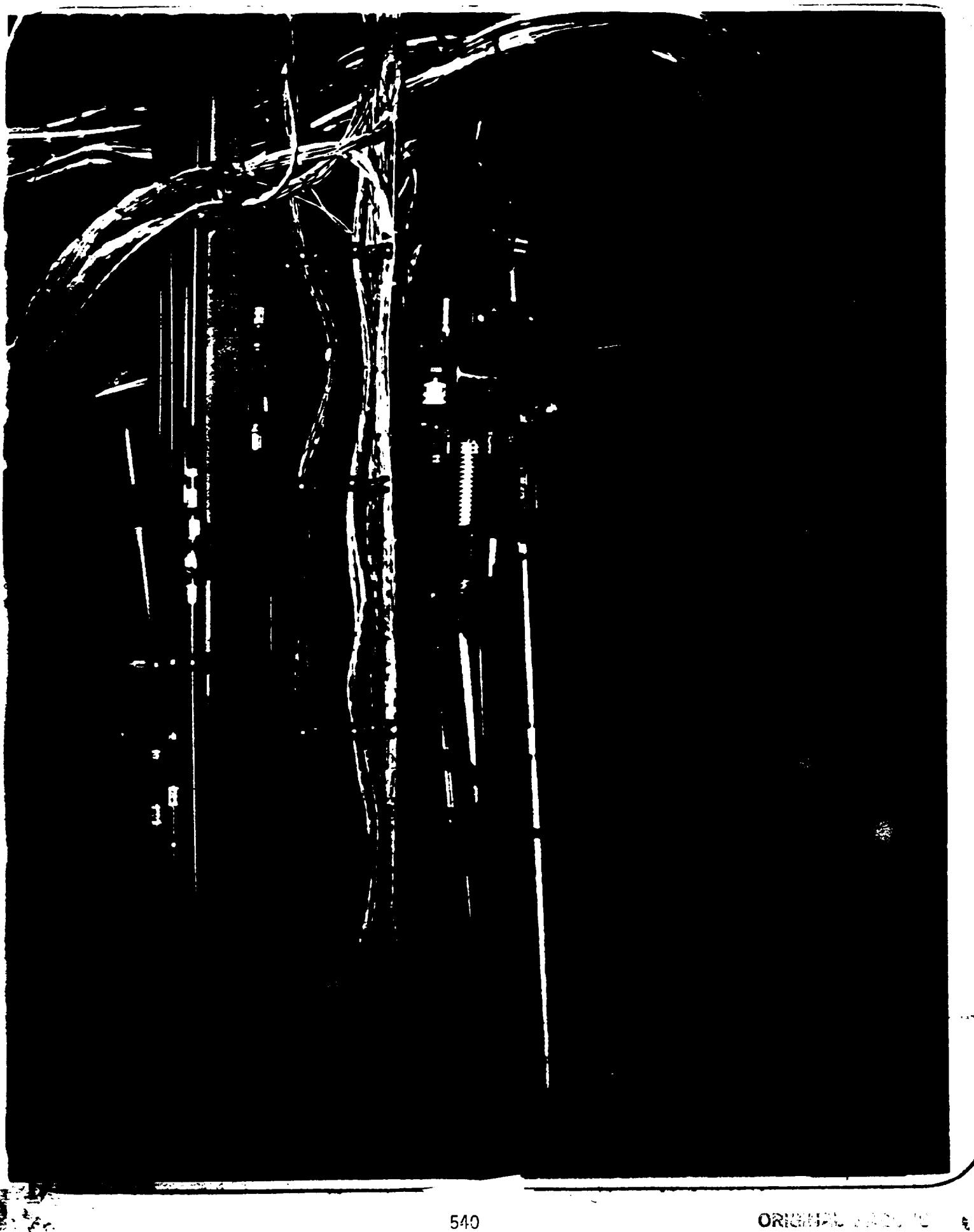
Lockheed
Aeronautical Systems Company
Marietta, Georgia

ELECTRO-HYDROSTATIC ACTUATION (EHA)



ORIGINAL EDITION OF THIS DRAWING
OF PAPER SIZE

SERVO MOTOR TYPE INTEGRATED ACTUATOR
BUILT BY PARKER-BERTEA AEROSPACE



EHA/HTTB FLIGHT TESTING OBJECTIVES

Maneuvers were performed consisting of: high rate '30 to 30' rolls at various airspeed/altitude combinations, take-offs & landings, precise aileron commands, and asymmetric thrust & sideslip maneuvers

- Measure response of the EHA subsystem to small, precise inputs and large, rapid inputs from the pilot
- Compare dynamic response characteristics of the EHA powered aileron to the unmodified aileron
- Produce sustained high hinge moment, requiring a holding output force from the EHA subsystem
 - pull back No. 1 & 2 engines to flight idle
 - input rudder as required to control yaw
 - trim ailerons to maintain approx. wings level

LASC CONCLUSIONS

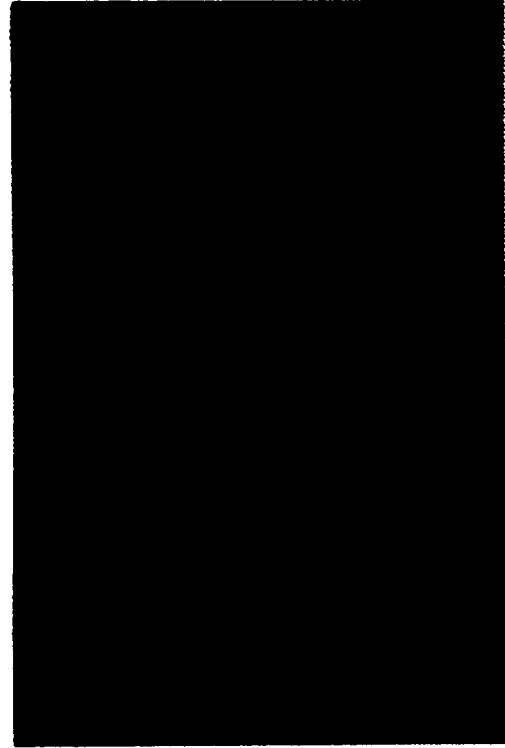
EHA SUBSYSTEM PERFORMANCE WAS EXCELLENT

- All Test Requirements Were Met
- EHA-Powered Aileron Performed Identically To The Existing Hydraulic Power Control Unit
- No Deviations Or Anomalies Were Encountered By The Pilots Or Test Engineers
- No Nuisance Shutdowns Or EHA Subsystem Faults Encountered During The Entire Test Program
- No Problems With Thermal Characteristics, Continuous Load Holding Or EMI

Lockheed involvement

POWER-BY-WIRE

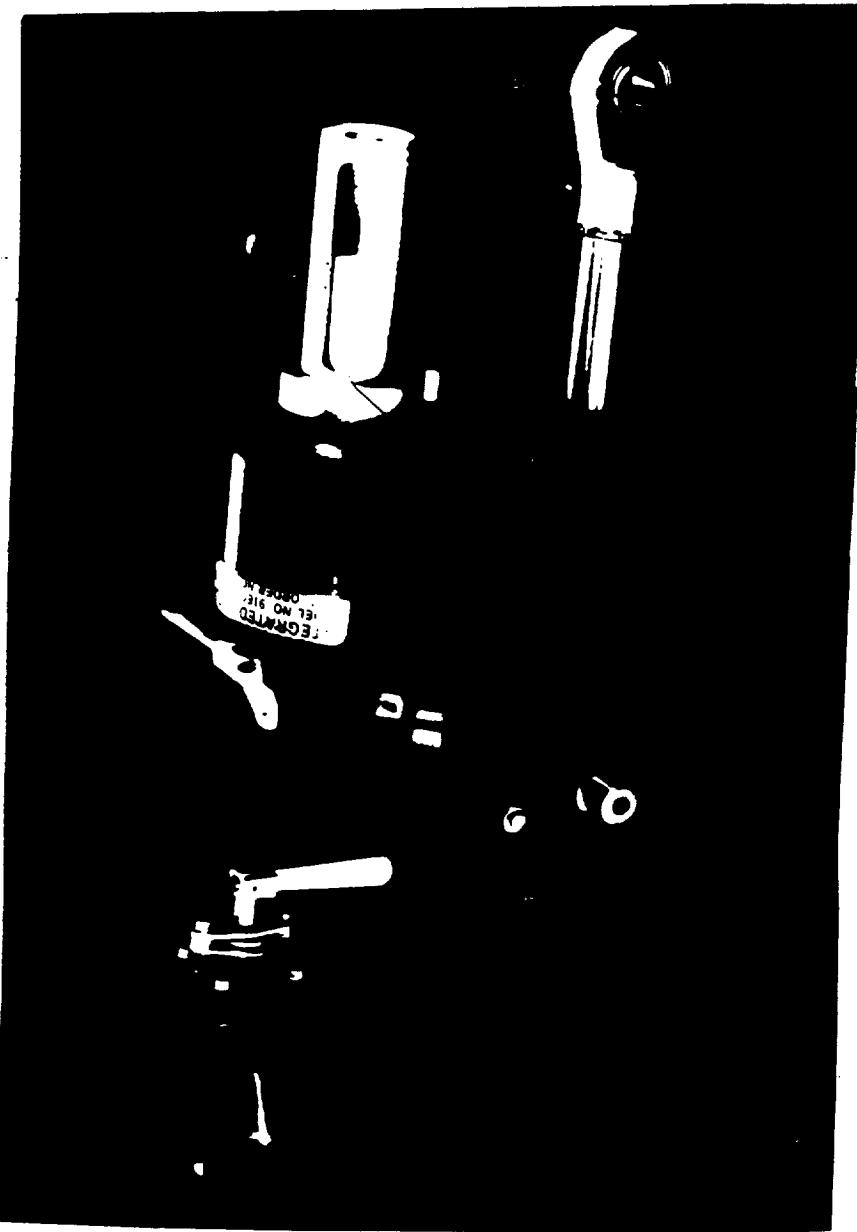
INTEGRATED ACTUATOR PACKAGE



- System Developed By Lucas Aerospace
- Flown on HTTB Rudder 10 Mar 1992 - Industry First Flight Test of an IAP
- An Industry CRAD Program, \$0.3M

 Lockheed
Aeronautical Systems Company
Munitions Division

INTEGRATED SERVO ACTUATOR



SERVO PUMP TYPE INTEGRATED ACTUATOR
BUILT BY LUCAS AEROSPACE

ACTIONS TAKEN

- OC-ALC/LII MST TAPM OFFICE INITIATED PROGRAM (1989)
 - INVESTIGATE DECOUPLING AILERON SYSTEM
 - POWER-BY-WIRE ACTUATION (MATURING PARKER BERTEA EHA)
 - FIRST FLIGHT 12-91 ON HTTB LEFT AILERON
- PROGRAM CONTINUATION
 - FRACAS (MIL-STD-2156) TESTS ON CONTRACT 9-92
 - ESTIMATED COMPLETION 5-93

POWER-BY-WIRE

The Future

Post "Electric Starlifter" RAMTIP - retrofit 13 Special Operations Low Level (SOLL) C-141 aircraft - about \$40M - in the WRAIC Weapon System Master Plan.

C-141 SLEP - incorporate Power-By-Wire spoiler flight control system.

C-130 Production - insert a version of the IAP into the rudder primary flight control system.

Next model C-130 - utilize IAPs on all three primary surfaces - elevator, rudder, and ailerons for improved R&M, flight safety, and survivability.

More-Electric Airplane - \$175M joint services/NASA program to flight test demonstrate several modern electric technologies including Power-By-Wire.

Future Lockheed Aircraft - AX, ATTR, Multi-Role Fighter, etc.

SESSION VIII

ELA PROTOTYPE DESIGNS & TEST RESULTS

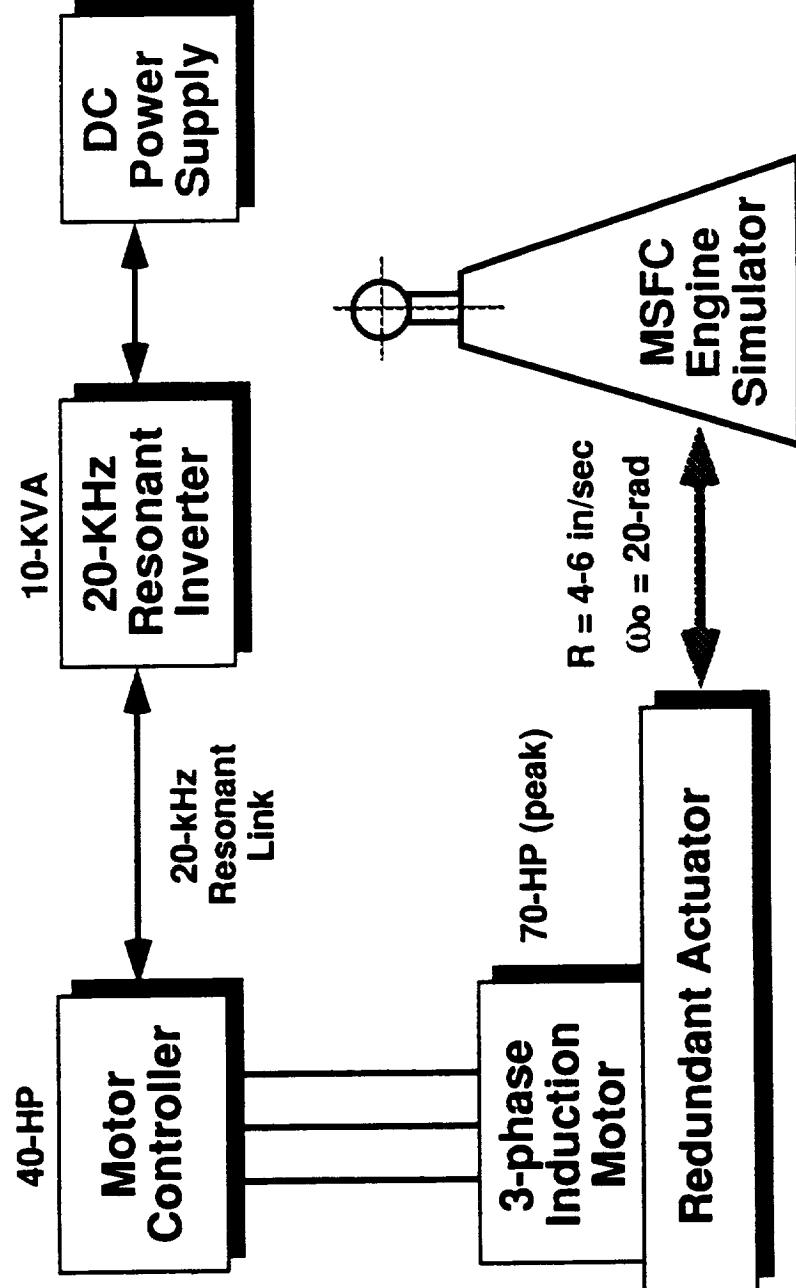
General Dynamics EMA Testing at NASA MSFC

Jim Mildice

**General Dynamics
Space Systems Division**

General Dynamics EMA Testing at MSFC

Test System Description



General Dynamics EMA Testing at MSFC

Motor Controller Design - (*General Dynamics*)

- **Power Output Stage**
 - Three-phase, bidirectional motor interface
 - High-frequency (20-KHz) AC power input
 - Bilateral output switches, to perform integral, synchronized AC input rectification, and low-frequency motor current synthesis and control
 - Pulse-population regulation, with zero current switching
- **Control**
 - Embedded microprocessor control for all functions except motor current regulation
 - Software in ROM
 - Analog motor current regulation loop, with computer-generated reference
 - All communications and interfaces via serial data busses

General Dynamics EMA Testing at MSFC

Motor Controller Capability

- **Power Inputs**
 - Power Stage Voltage = 300-V_{RMS}, single-phase, AC
 - Frequency = 20-KHz
 - Total Power = 44.0-KVA (maximum)
- **Command Inputs**
 - Digital, serial data bus - RS-232
- **Feedback**
 - Analog, motor resolver outputs
 - Analog, motor current
- **Outputs**
 - Variable Voltage = zero to 200-V_{RMS}, L-L; three-phase AC
 - Variable Frequency = zero to 750-Hz
 - Power = 40-KVA (maximum)

General Dynamics EMA Testing at MSFC

Induction Motor - (Sunstrand)

- **Electrical Characteristics**

- Input Voltage = 115-volt, RMS,L-N; three-phase
- Input Frequency at Full Speed = 750-Hz
- Power Factor = 0.753
- Efficiency = 89.9%

- **Mechanical Characteristics**

- Rated Power = 69.3-HP(peak); 34.6-HP(steady state)
- Full Rated Speed = 14,700RPM @ Full Load
- Operating Torque = 148.4 in-lb
- Maximum Torque = 400 in-lb
- Specific Weight = 3.32-HP/lb(peak); 1.7-HP/lb(steady state)
- Specific Volume = 1.6-HP/cu.in(peak); 3.1-HP/cu.in(steady state)
- Moment of Inertia = 0.0103 in-lb-sec-sec

General Dynamics EMA Testing at MSFC

Redundant Actuator - (Moog)

- **Performance**
 - Force Rating = 48,000-lb (operating); 100,000-lb (maximum)
 - Extension = ± 5.4 -inches
 - Maximum required Rate = 7.4-inches/second
 - Engine Start Transient relief = force feedback with integral load cell
- **Mechanical Design**
 - Design compatible with roller screw or ball screw output
 - Dual (redundant) motor mounts with torque summing in the gear train (no mechanical decoupling)
 - Length = 47.33-inches, pin-to-pin
 - Weight = 300-lb (non-optimized prototype)
 - Moment of Inertia (at the motor shaft) = 0.0089 in-lb-sec-sec

General Dynamics EMA Testing at MSFC

Tests Performed

- **Compatible Operation**
 - Low power test to verify EMA/Controller/Facility compatibility
 - Full power operation to verify EMA/Controller/Facility compatibility
- **Step Response**
 - Step function position commands from (+) to (-) 0.05- to 2.5-inches
 - Maximum rate achieved \approx 6-inches/second (consistent with input power limitation)
- **Frequency Response for various displacements**
 - Combinations of frequencies and displacements from 0.1-Hz @ \pm 0.05-inch to 4.0-Hz @ \pm 0.25 inch
 - Small signal bandwidth \approx 20-radians
 - Typical power (slew rate) limited frequency response \approx 2.0-Hz @ \pm 0.5-inches

General Dynamics EMA Testing at MSFC

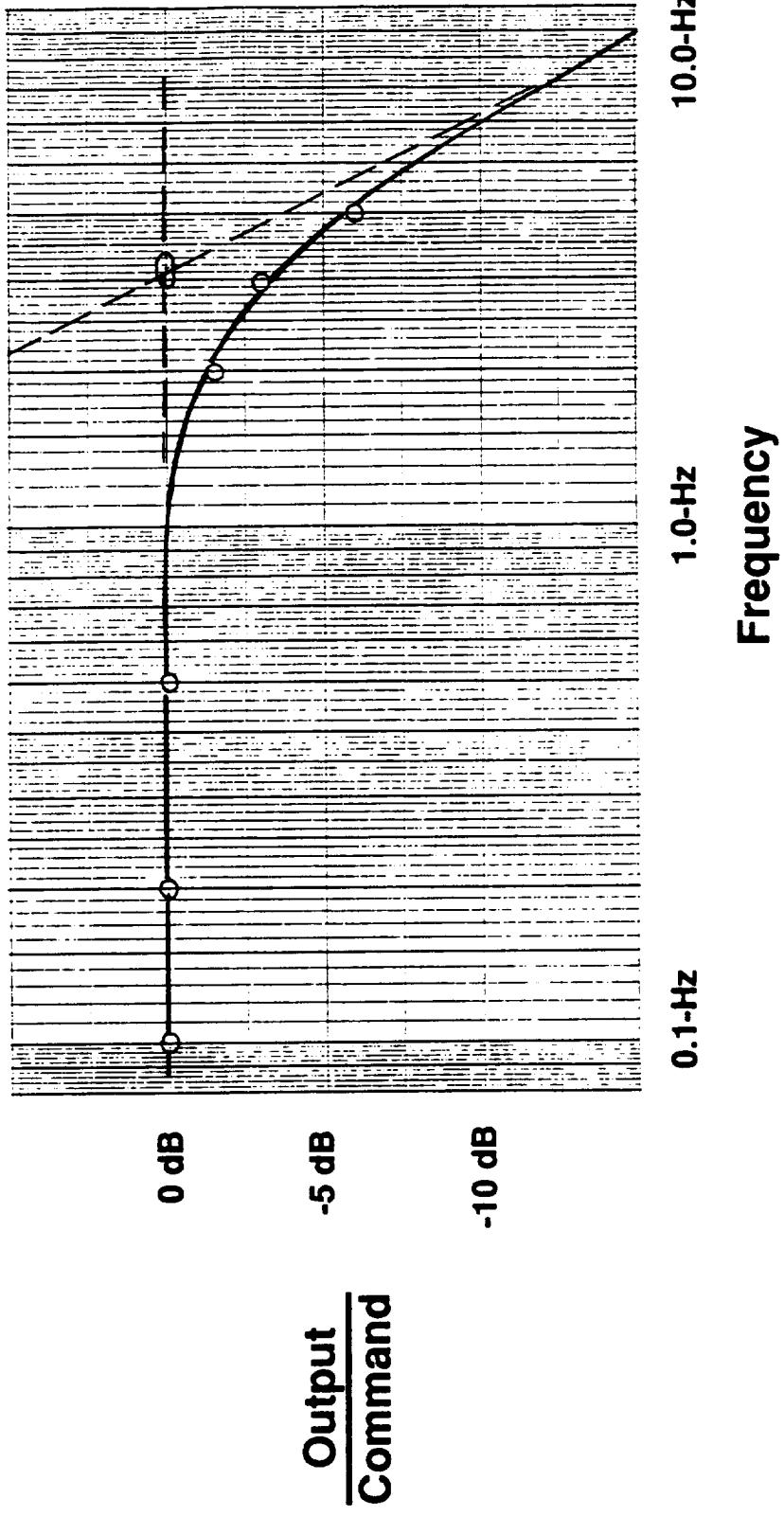
Special Conditions and Limits

(for This Test Only)

- Engine position control loop **software/system response designed to NLS-2 requirements**
 - Position control loop bandwidth limited to 20-radians
- **High-frequency AC controller input power limited to 10-KVA by the inverter capability**
 - Step response limited to approximately 6-inches/second
 - Large signal frequency response is slew-rate limited.
Limiting typically starts at about 2.0-Hz @ ± 0.5 -inches

General Dynamics EMA Testing at MSFC

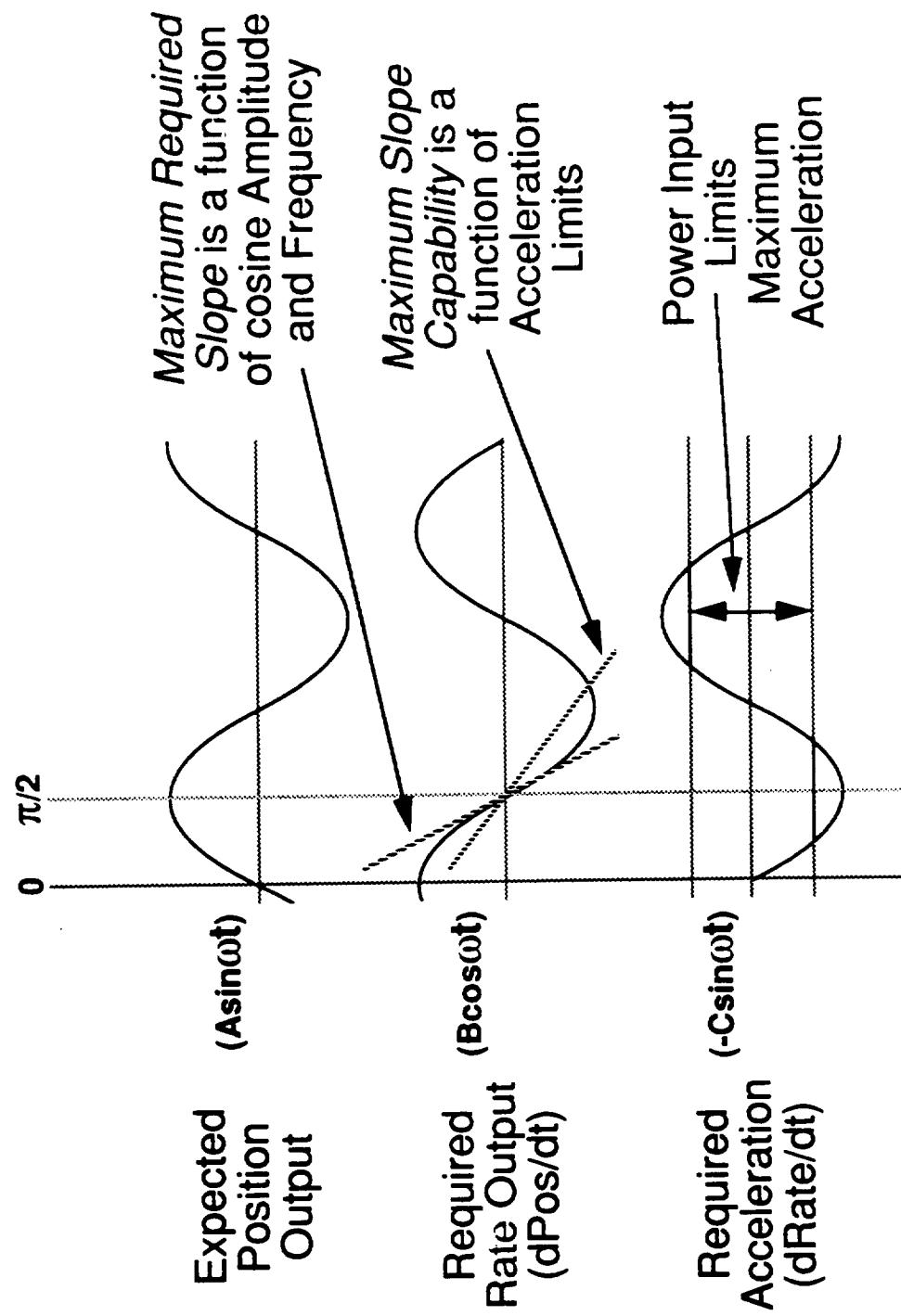
Small Signal Frequency Response



Data is consistent with the design for a critically-damped, second-order system with a 20-radian (3.2-Hz) bandwidth

General Dynamics EMA Testing at MSFC

Frequency Response Limit



General Dynamics EMA Testing at MSFC

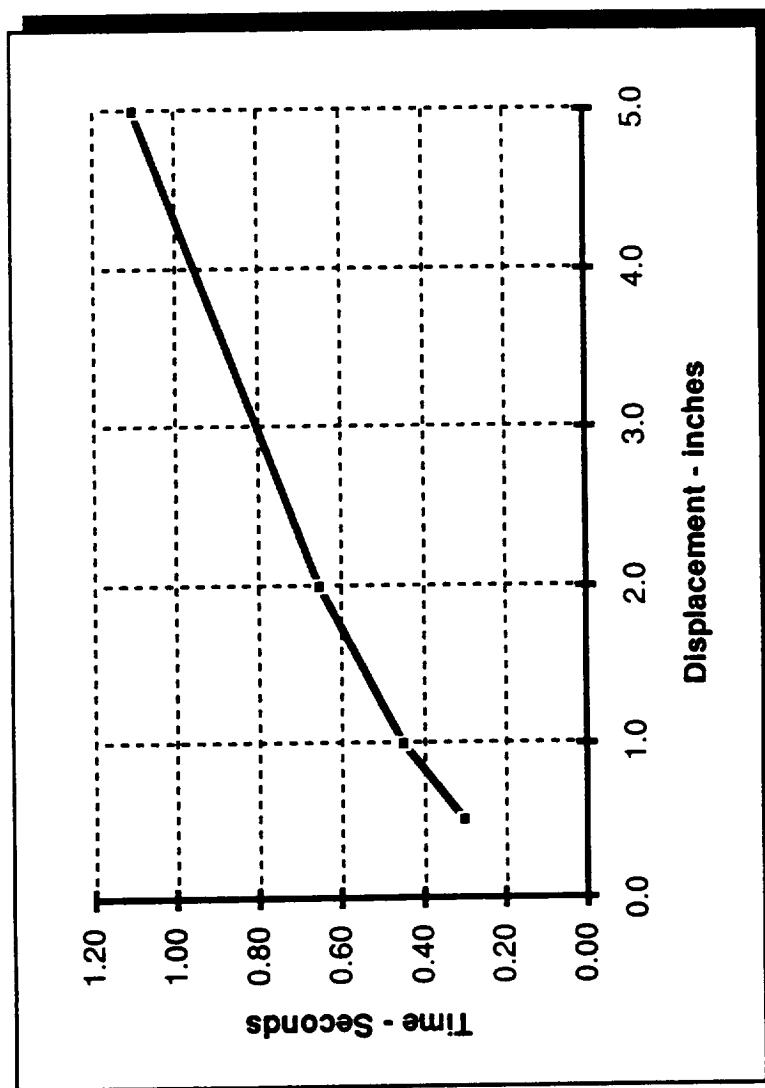
Frequency Response

- Limited input power limits the torque available for acceleration
 - $\text{Torque}(\text{accel}) = \text{Torque}(\text{total}) - \text{Torque}(\text{load+friction})$
- At the limit, acceleration is constant, the maximum rate change slope is constant, and the system becomes “slew rate” limited
- The constant value rate change slope, for a “slew rate” limited system (*Maximum Slope Capability*) must be larger than the *Maximum Required Slope for the rate output*
 - If it is not, the output amplitude is limited
- After we work through the math, Slew Rate limit for frequency response is:

$$f_{SR} \leq \frac{SR}{(2\pi \times B_{pk})}$$

General Dynamics EMA Testing at MSFC

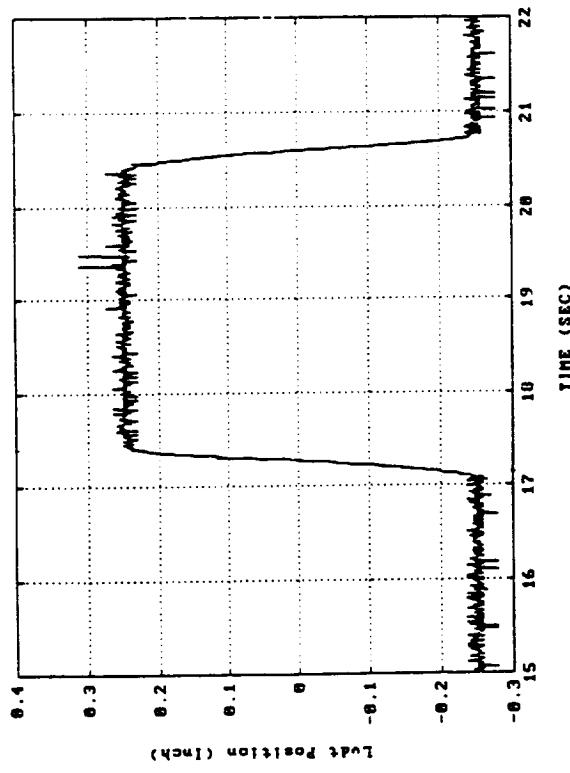
Step Response Average Rates



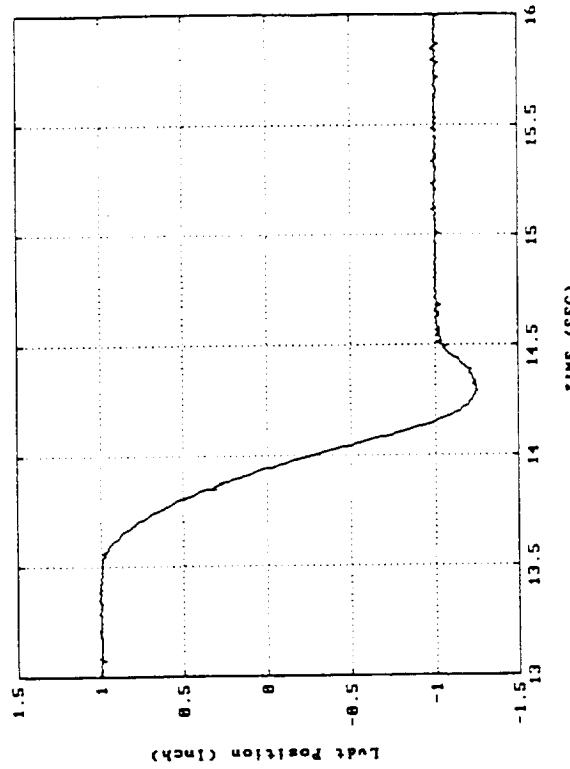
Step Response is consistent with power limits

General Dynamics EMA Testing at MSFC

Step Response Typical Characteristic



**Step = 0.5-inches
Max Rate = 4.5-in/sec
(no power limiting)**



**Step = 2.0-inches
Max Power-limited
rate = 6.0-in/sec**

General Dynamics EMA Testing at MSFC

Summary

- General Dynamics EMA testing at MSFC was satisfactorily completed during the week of September 8-11
- Evaluated test results were within expected ranges
 - Small-signal bandwidth \approx 20-radians
 - Power-limited maximum rate \approx 6.0-inches/second
 - Accuracy & Linearity are better than the resolution of the data
- Maximum potential capability was not demonstrated due to the following:
 - Control system bandwidth was designed to meet the NLS-2 requirement of 20-radians
 - Motor controller power input was limited by the capability of the source, which resulted in a limited large-signal amplitude-bandwidth

MSFC IN-HOUSE ACTUATOR TEST RESULTS

SYSTEM DESIGN SPECIFICATIONS

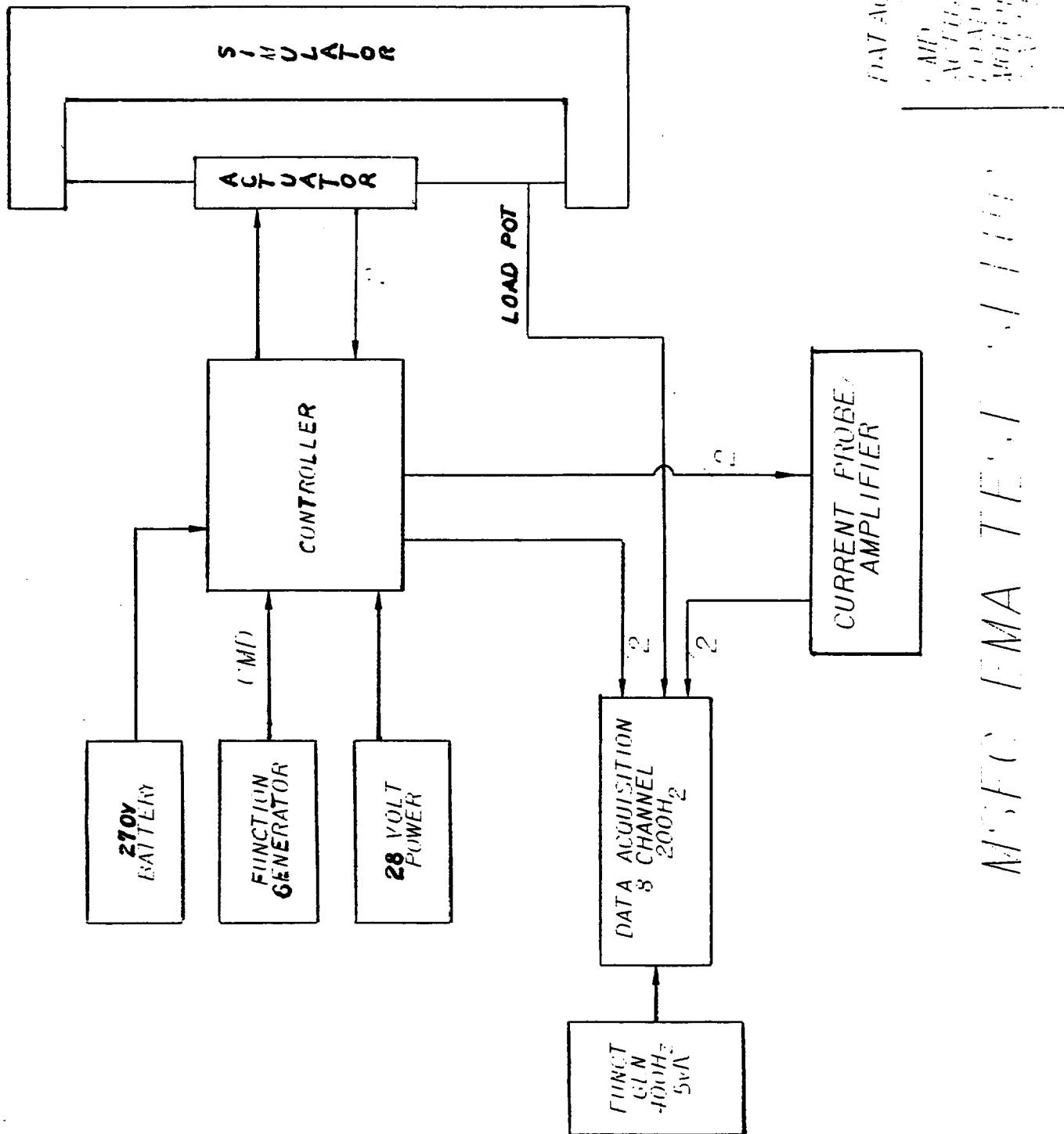
- 3 Hz. Bandwidth (2 to 5% of full stroke)
- Less than 25 degrees of Phase Lag at 1 Hz.
- .050 in. accuracy
- Rate of 5 in/sec.
- Less than 20% overshoot
- Load of 35,000 lbs.

A MSFC TEST PLAN WAS WRITTEN TO COMPLY WITH THE ELA ROCKWELL DEVELOPED ACTUATOR TEST PLAN. DUE TO A FAILURE OF THE LOAD-VS-RATE TEST BED, THE LAST TWO TESTS WERE NOT PERFORMED. UPON MODIFICATION OF THE TEST BED, THESE TESTS WILL BE RUN AND THE RESULTS DOCUMENTED.

MSFC TVC ACTUATOR TEST PLAN

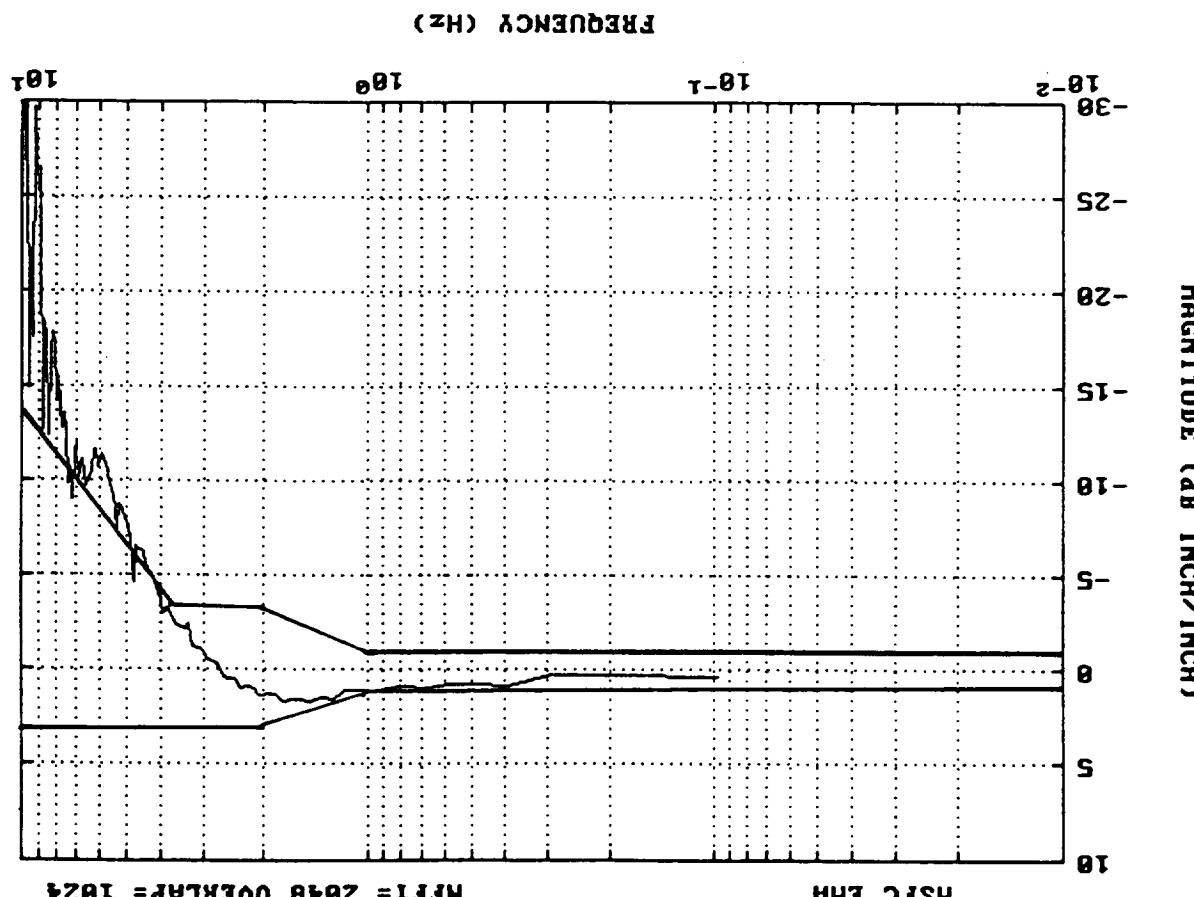
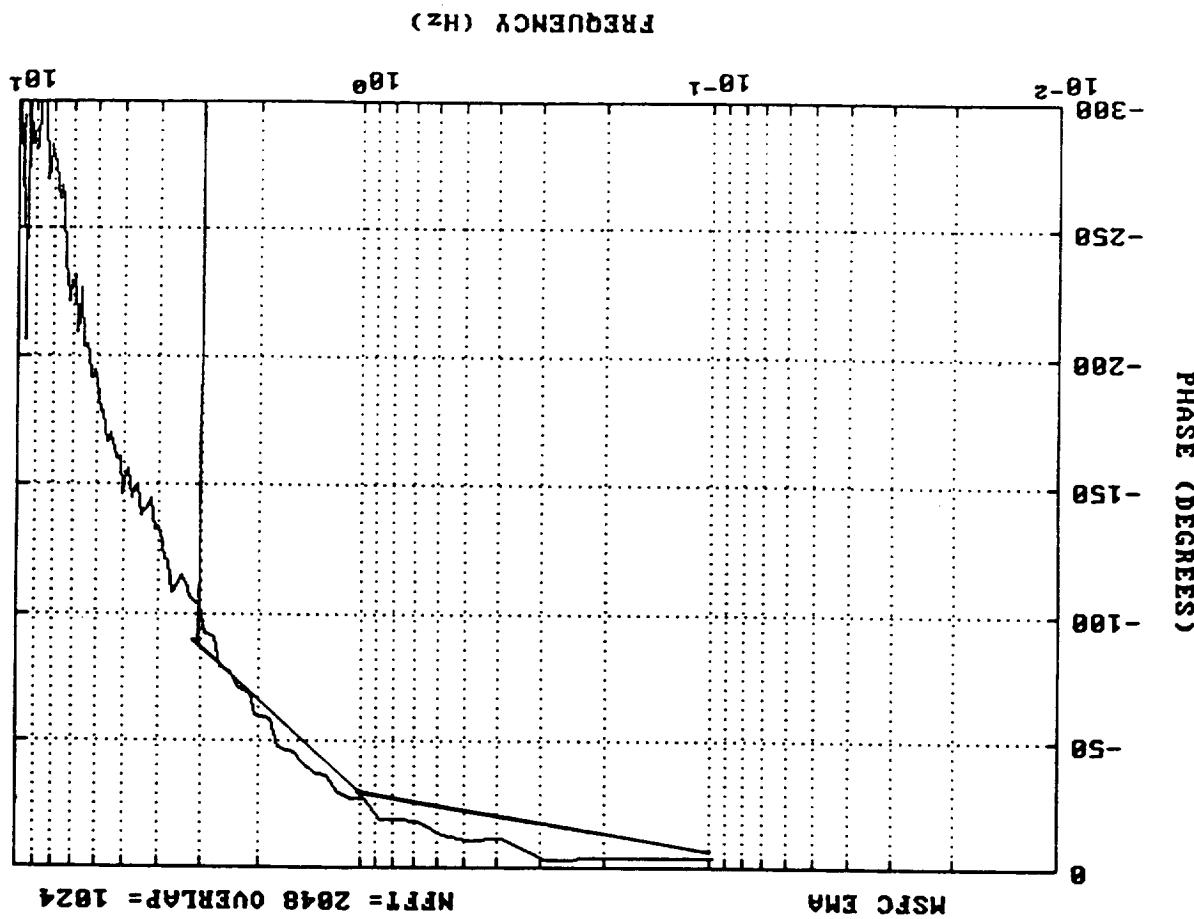
- Frequency Response Tests
- Linearity/Hysteresis Tests
- Step Response Tests
- Rate -vs- Load Tests
- Backdrive and Breakaway Friction Tests

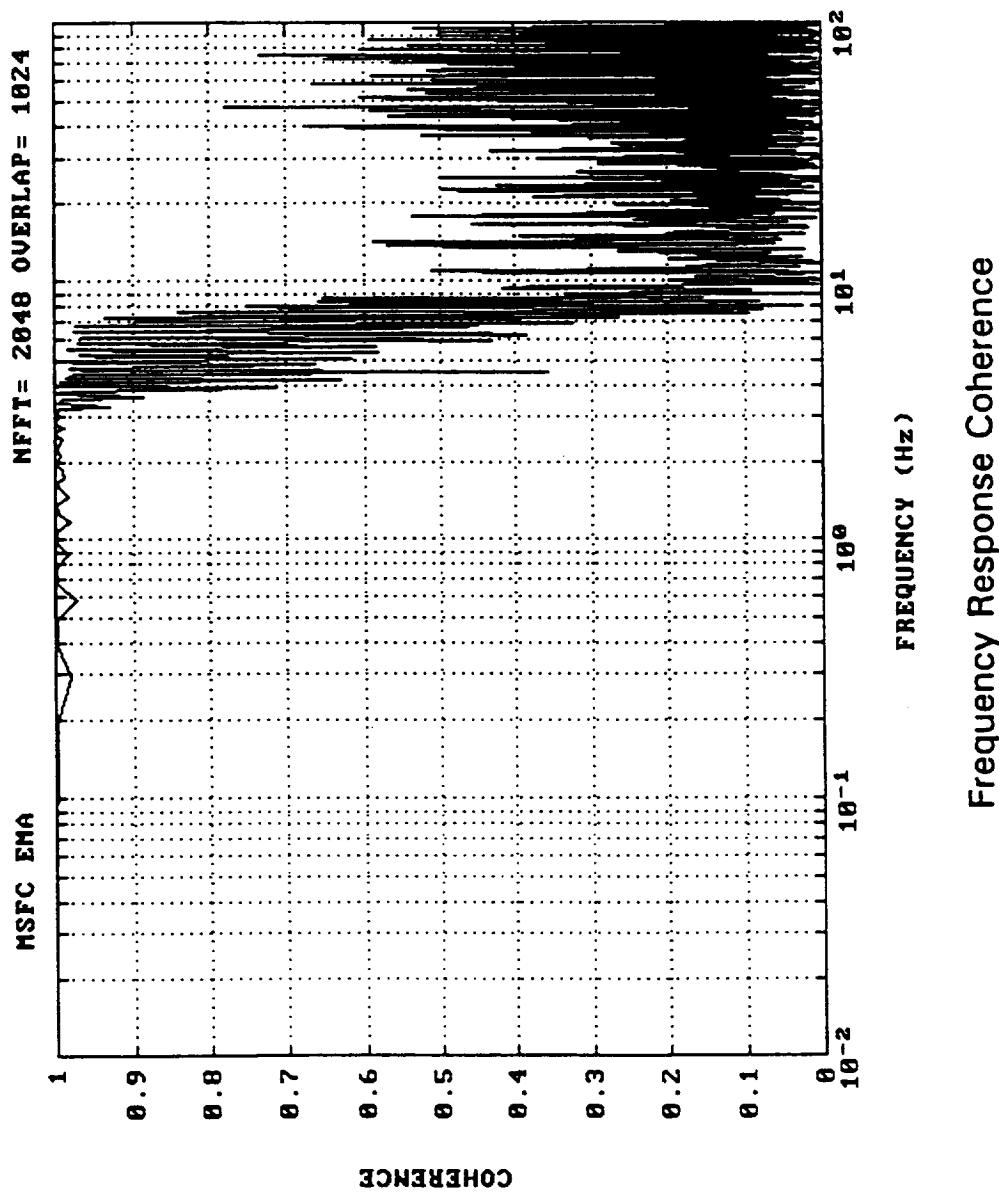
THIS IS A BLOCK DIAGRAM OF MSFC'S TEST SETUP. HIGH POWER WAS PROVIDED FROM A 270 VOLT BATTERY BANK AND LOW OR AVIONIC POWER FROM A 28 VOLT POWER SUPPLY. COMMAND WAS PROVIDED BY A FUNCTION GENERATOR OR IT WAS COMPUTER GENERATED. THE ACTUATOR WAS MOUNTED IN THE INERTIA LOAD SIMULATOR. THE CONTROLLER RECEIVES TWO SIGNALS (MOTOR COMMUTATION, ACTUATOR POSITION) FROM THE ACTUATOR. DATA ACQUISITION CONSISTED OF AN 8-CHANNEL SYSTEM WITH A 200 HZ SAMPLE RATE. DATA TAKEN INCLUDED COMMAND, ACTUATOR POSITION, LOAD POSITION, BATTERY CURRENT, AND MOTOR CURRENT.



THE ENVELOPE ON THE FREQUENCY RESPONSE CHART IS THE SSME SMALL SIGNAL REQUIREMENT. DATA SHOWS THE RESPONSE MEETS SSME SPECIFICATIONS. DATA ABOVE 4 OR 5 HZ HAS STARTED LOSING COHERENCE, AS CAN BE SEEN IN THE NEXT CHART. THE BANDWIDTH OF THE SYSTEM IS APPROXIMATELY 4 HZ. THE RESPONSE ALSO MEETS THE > -25 DEGREES OF PHASE LAG AT 1 HZ REQUIREMENT.

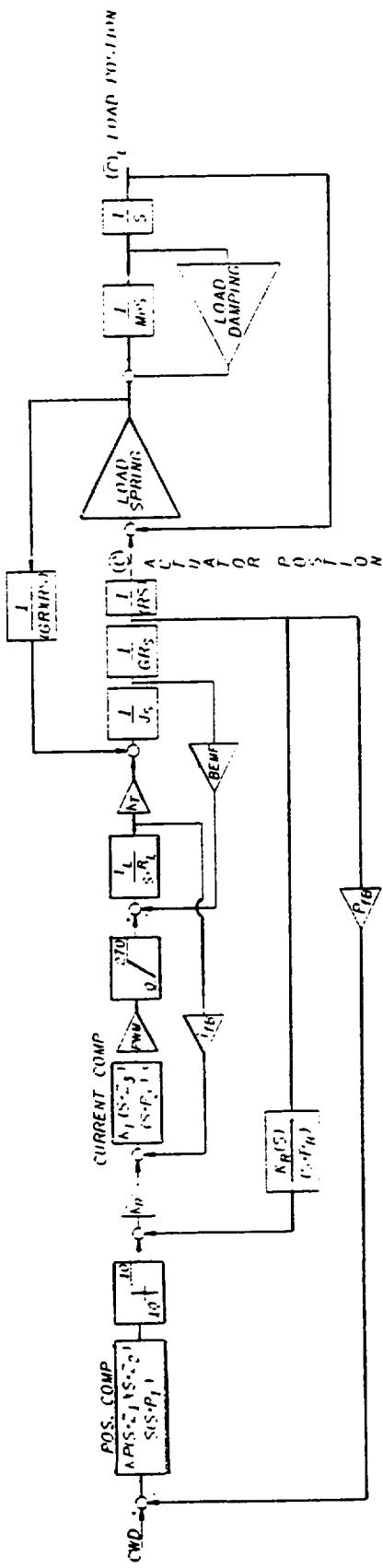
Frequency Response with SSM Envelope Requirements



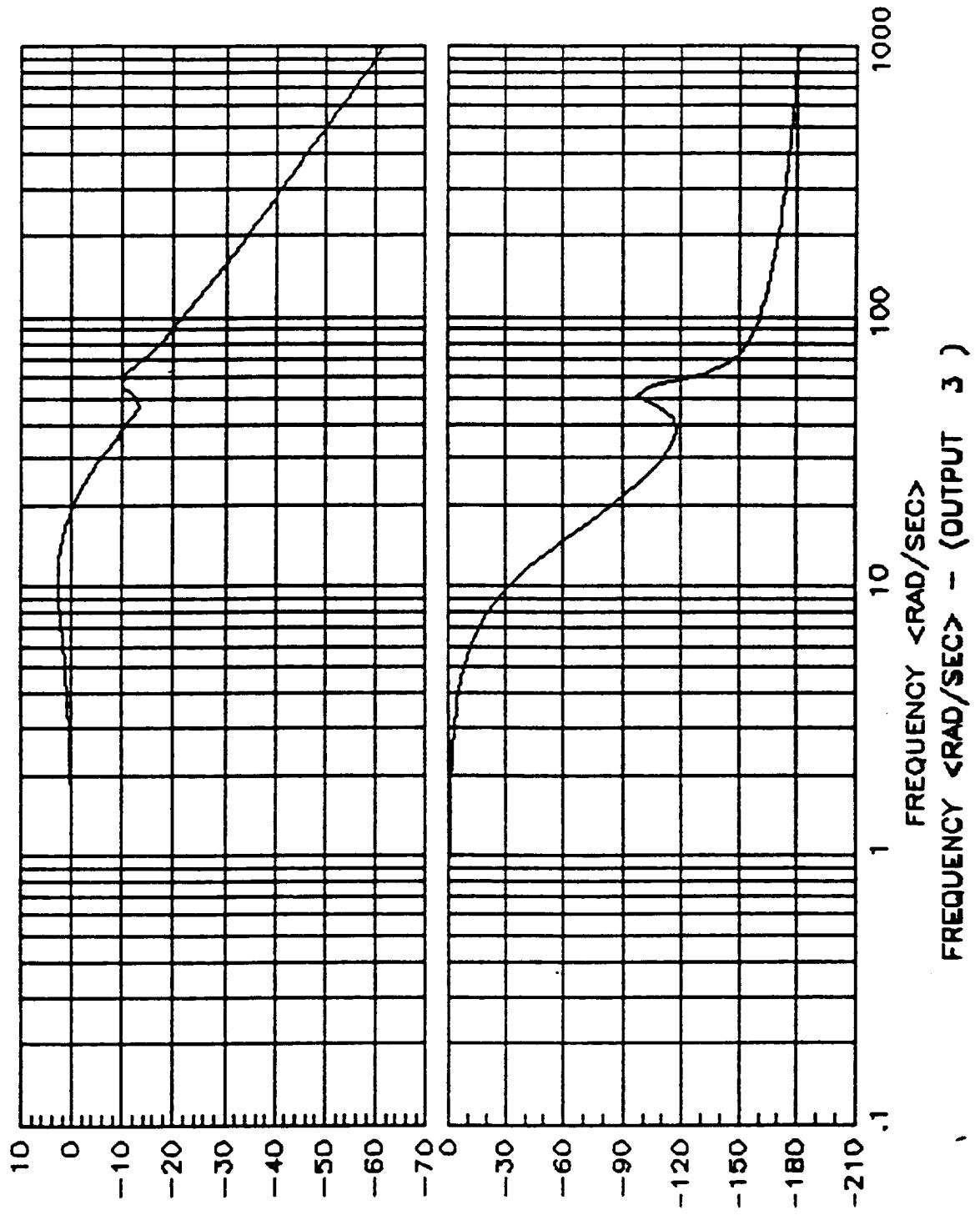


THE BASIC CONTROL SYSTEM BLOCK DIAGRAM SHOWS THE THREE CONTROL LOOPS (CURRENT, RATE, AND POSITION), ACTUATOR, AND LOAD. THE LOAD CORRESPONDS TO THE SSME WITH SLIGHTLY MORE DAMPING DUE TO FRICTION IN THE INERTIA LOAD SIMULATOR. THE FIRST SET OF DATA IS WITH A CONTROLLER CONFIGURATION LACKING THE RATE LOOP. TEST DATA IS LATER SHOWN, WHICH WAS TAKEN AFTER THE RATE LOOP WAS IMPLEMENTED.

THE NEXT VIEWGRAPH SHOWS THE SIMULATED FREQUENCY RESPONSE (FREQUENCY IN RADIANS). THE MODEL FOLLOWS ACTUAL TEST DATA CLOSELY.

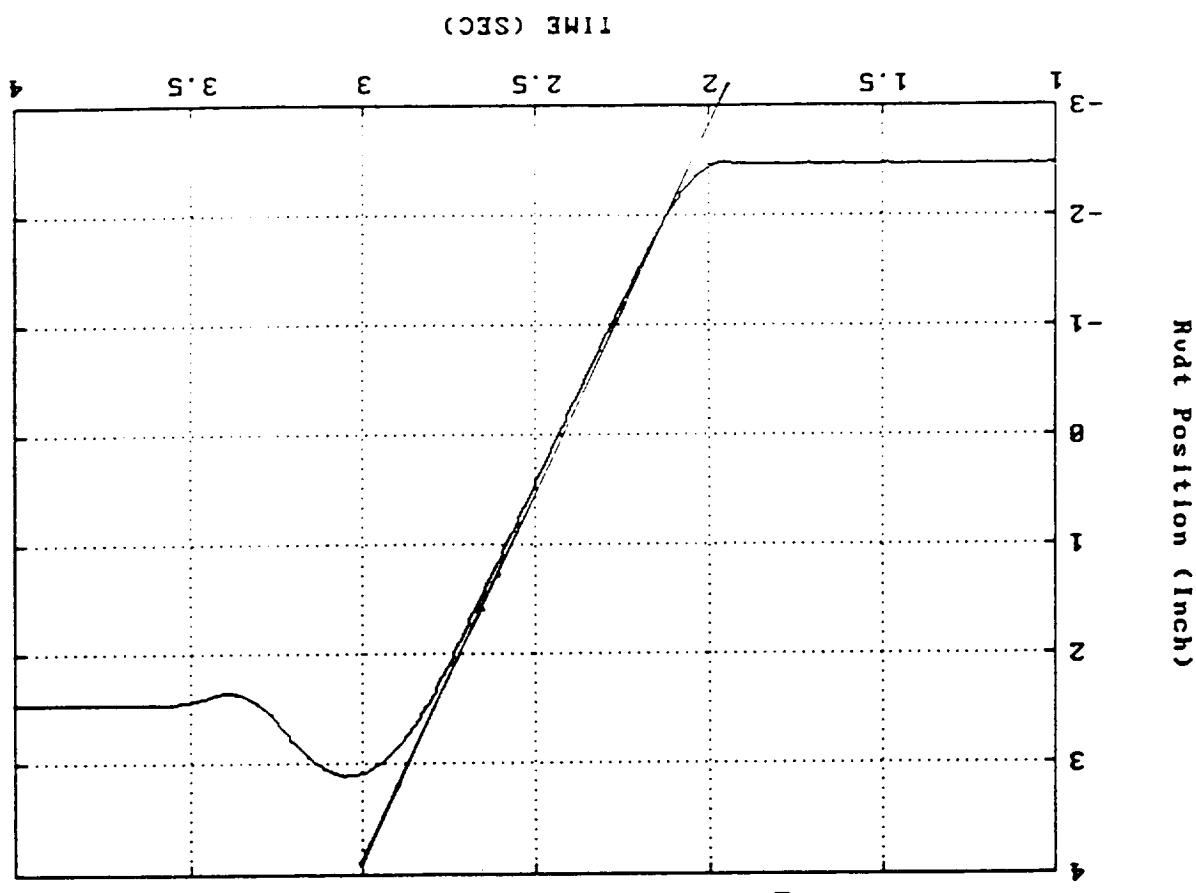


MSFC 25 H.P. Actuator System Block Diagram

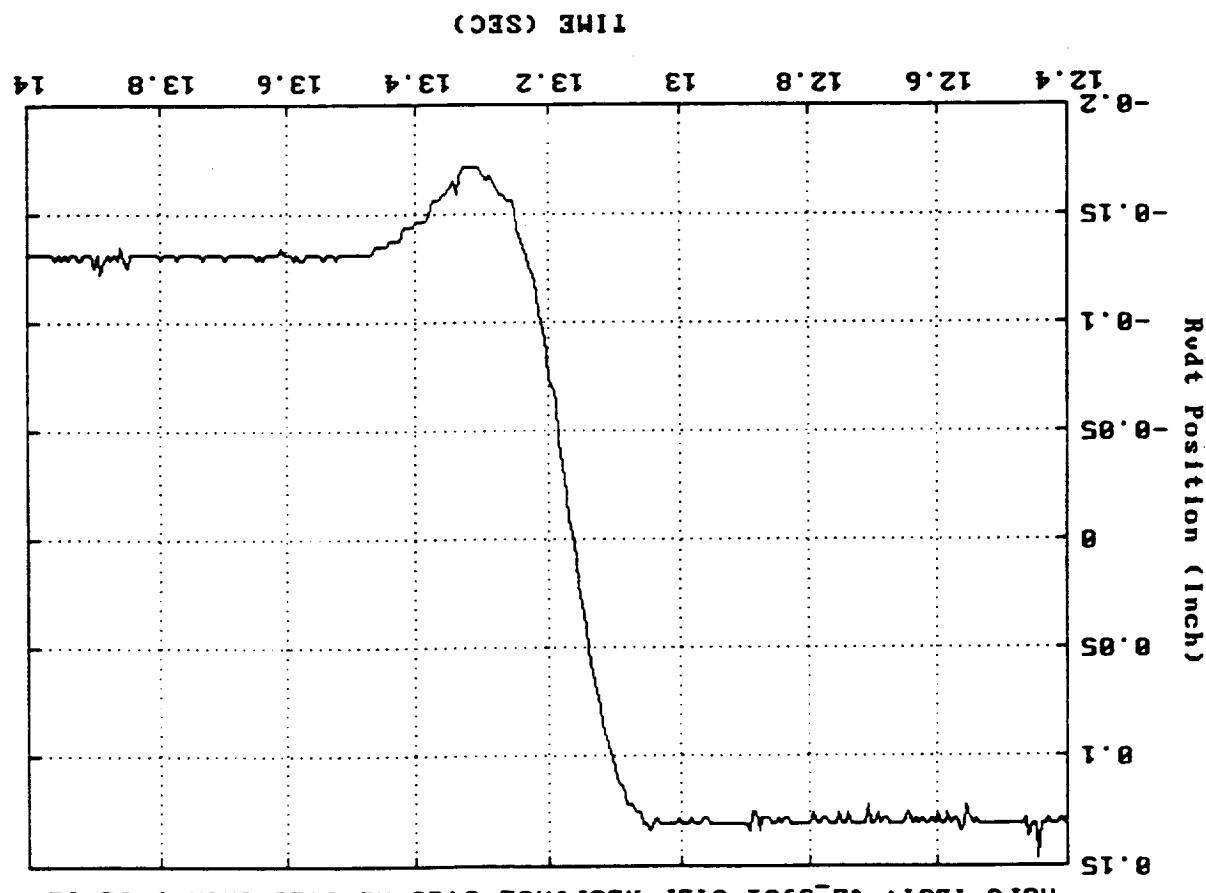


Simulated Frequency Response

THESE ARE EXAMPLES OF BOTH SMALL AND LARGE STEP RESPONSES. THE SMALL STEP SHOWS AN OVERSHOOT OF 16 PERCENT AND ALSO MEETS THE SSME SMALL STEP REQUIREMENTS. THE LAYER STEP HAS A 13 PERCENT OVERSHOOT. THE MAXIMUM RATE IS ALMOST 7 IN/SEC WHICH EXCEEDS THE DESIGN REQUIREMENT.



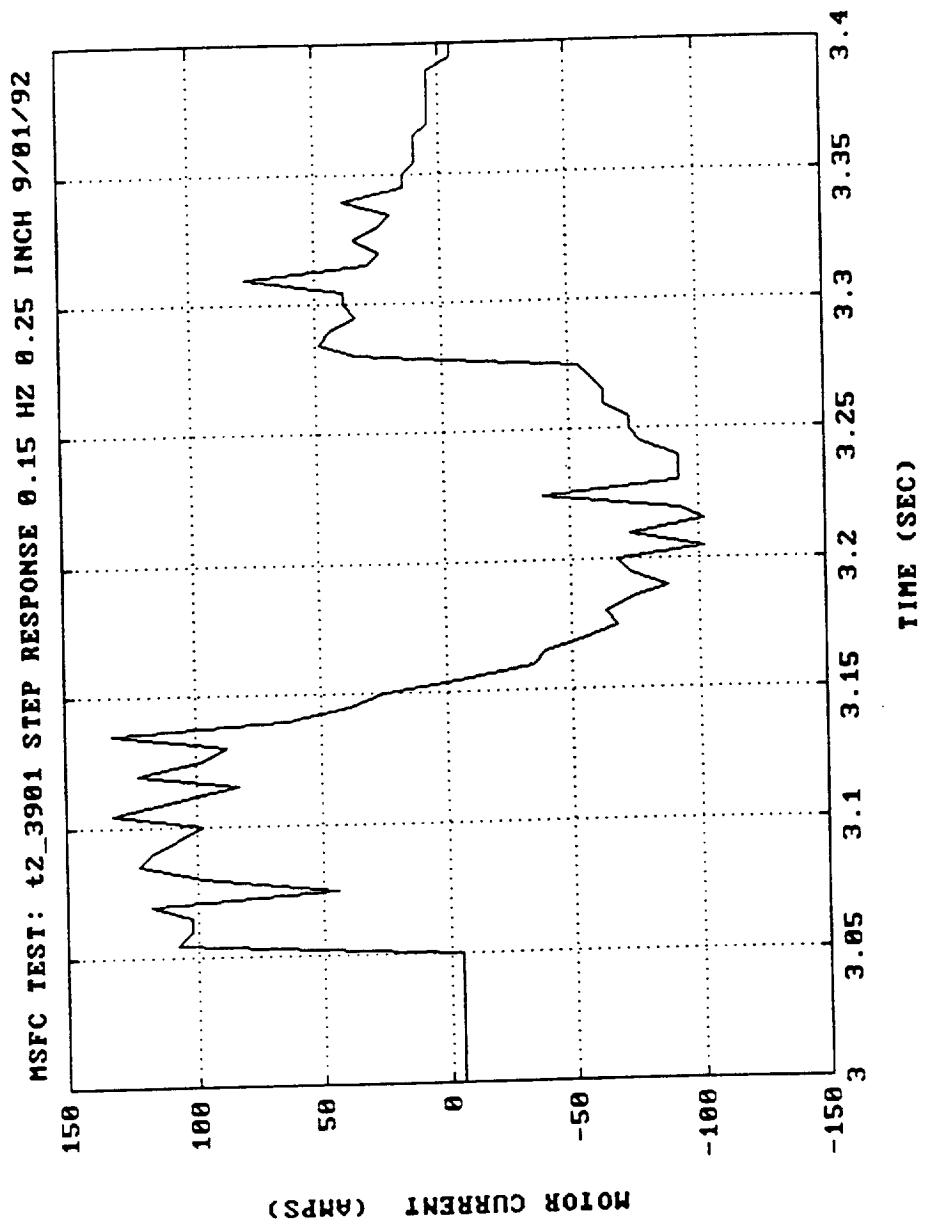
MSFC TEST: t2-8901 STEP RESPONSE 0.15 HZ 5 INCH 9/01/92

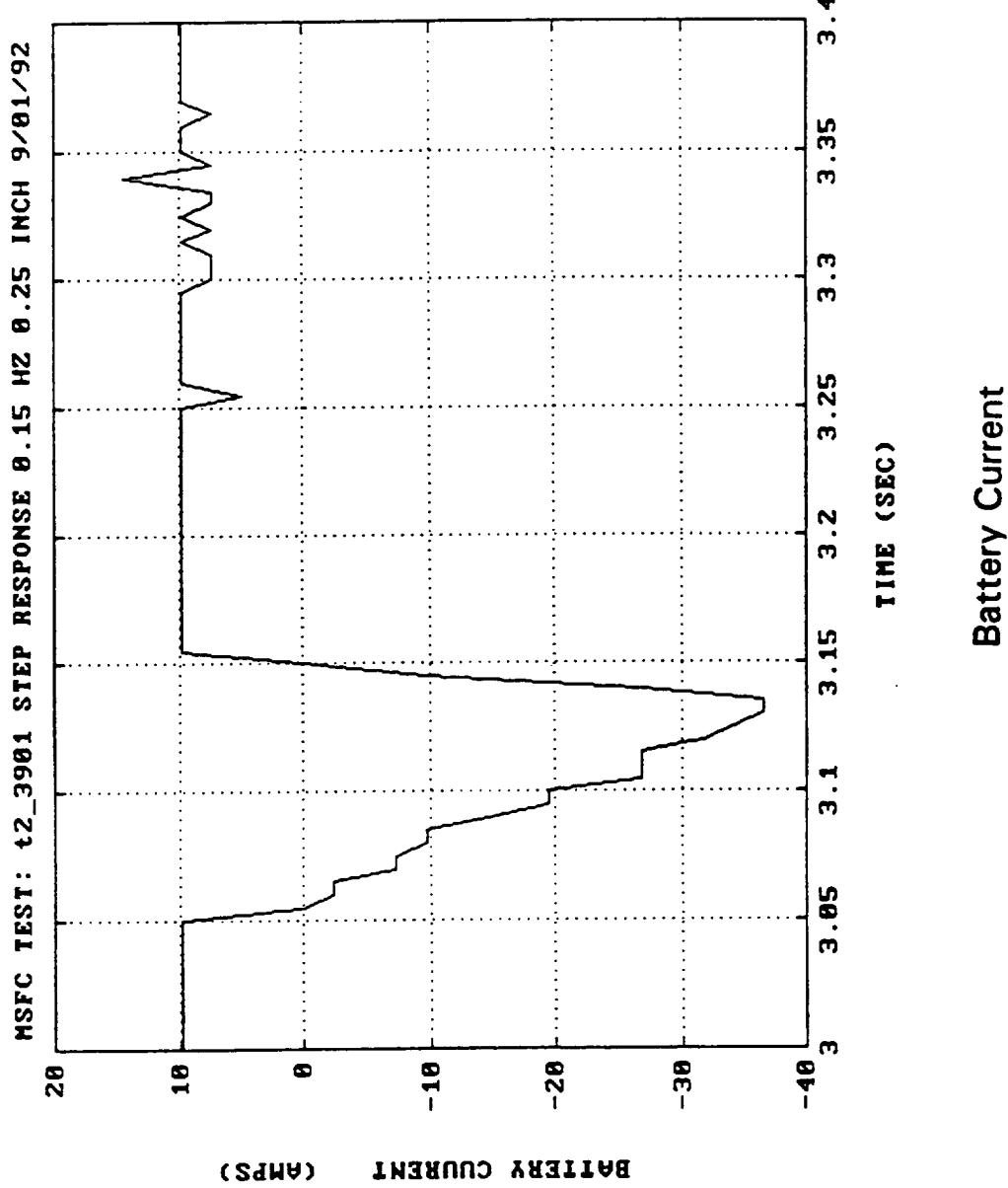


MSFC TEST: t2-3901 STEP RESPONSE 0.15 HZ 0.25 INCH 9/01/92

THE NEXT TWO VIEWGRAPHS COMPARE MOTOR AND BATTERY CURRENT FOR THE 0.25 INCH STEP. THE POLARITY ON BATTERY CURRENT IS REVERSED AND SLIGHTLY OFFSET, BUT THE TIME AXES ARE IDENTICAL. THIS SHOWS THAT THE CAPACITOR ON THE CONTROLLER ACCOMMODATES THE INITIAL CURRENT REQUIREMENT. ONE CAN SEE BATTERY CURRENT RAMPS UP AND THERE IS NOT A LARGE INSTANTANEOUS CURRENT DRAIN FROM THE POWER SOURCE. ALSO, NOTE THAT BATTERY CURRENT IS NOT REQUIRED DURING THE BRAKING PORTION OF THE STEP RESPONSE, EVEN THOUGH THE MOTOR ITSELF CONTINUES TO CARRY CURRENT IN THE REGENERATION MODE.

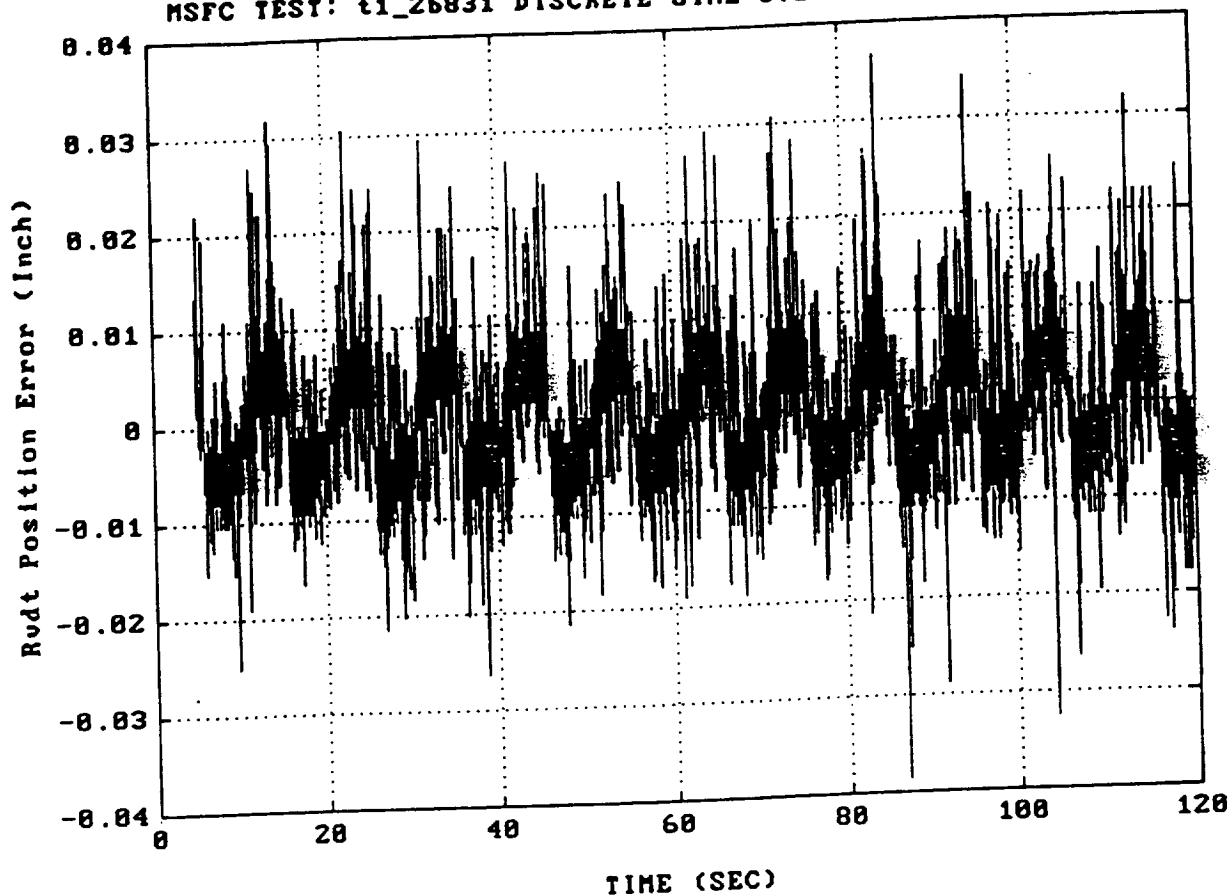
Motor Current



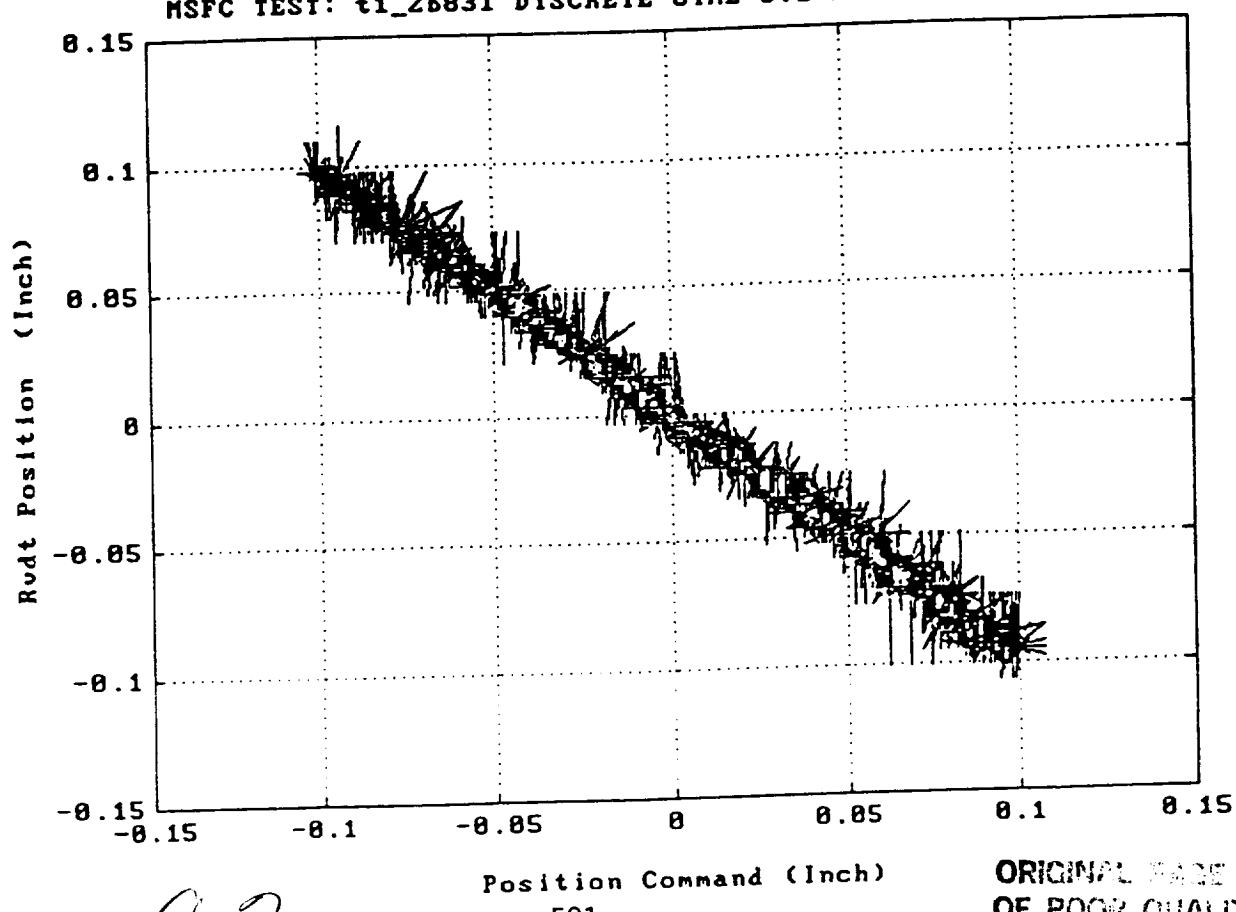


THE NEXT TWO VIEWGRAPHS SHOW LINEARITY FOR BOTH SMALL AND LARGE EXCURSIONS. THE POSITION ERROR FALLS WITHIN THE NOISE OF THE DATA AND MEETS THE 0.050 INCH ACCURACY REQUIRED, WITH THE LARGE EXCURSION ERROR BEING ABOUT 0.030 INCH.

MSFC TEST: t1_2b831 DISCRETE SINE 0.1 HZ 0.1 INCH 8/31/92

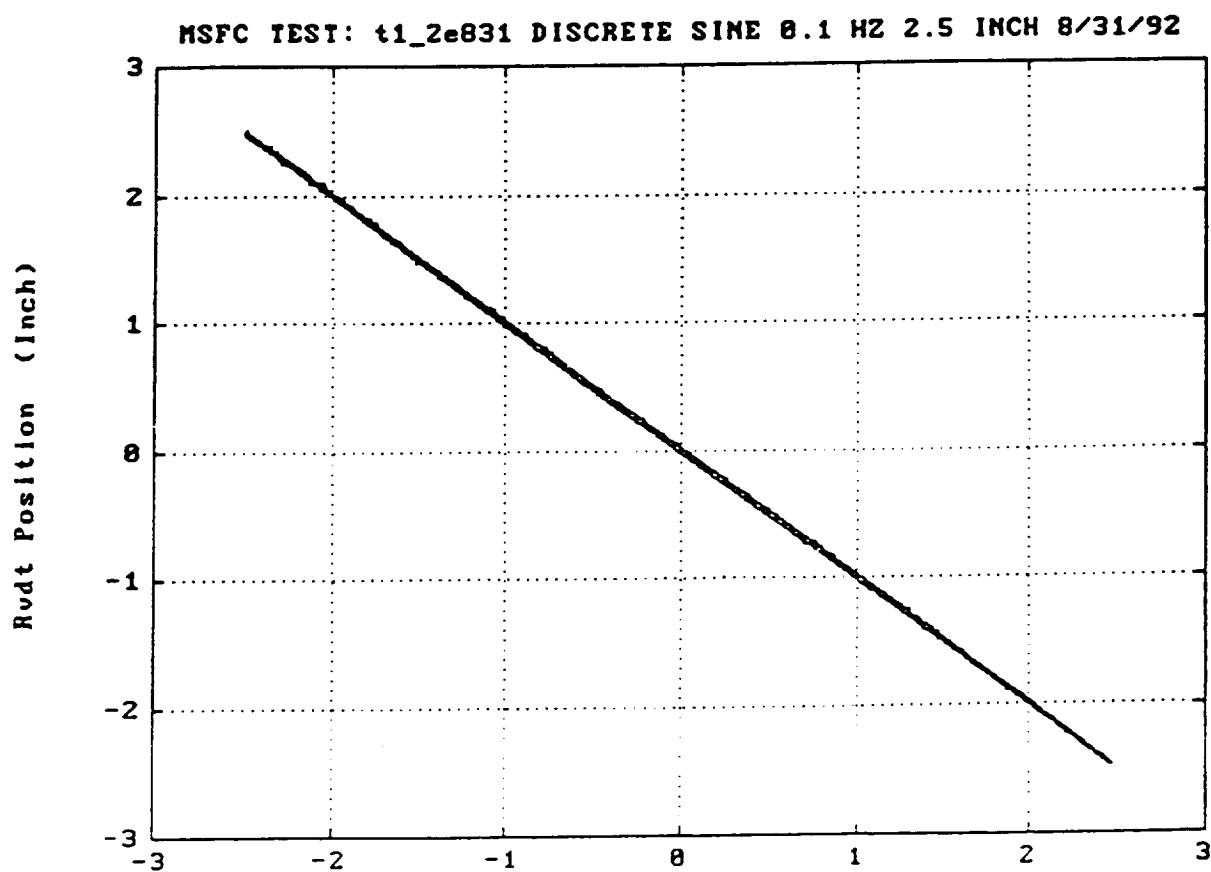
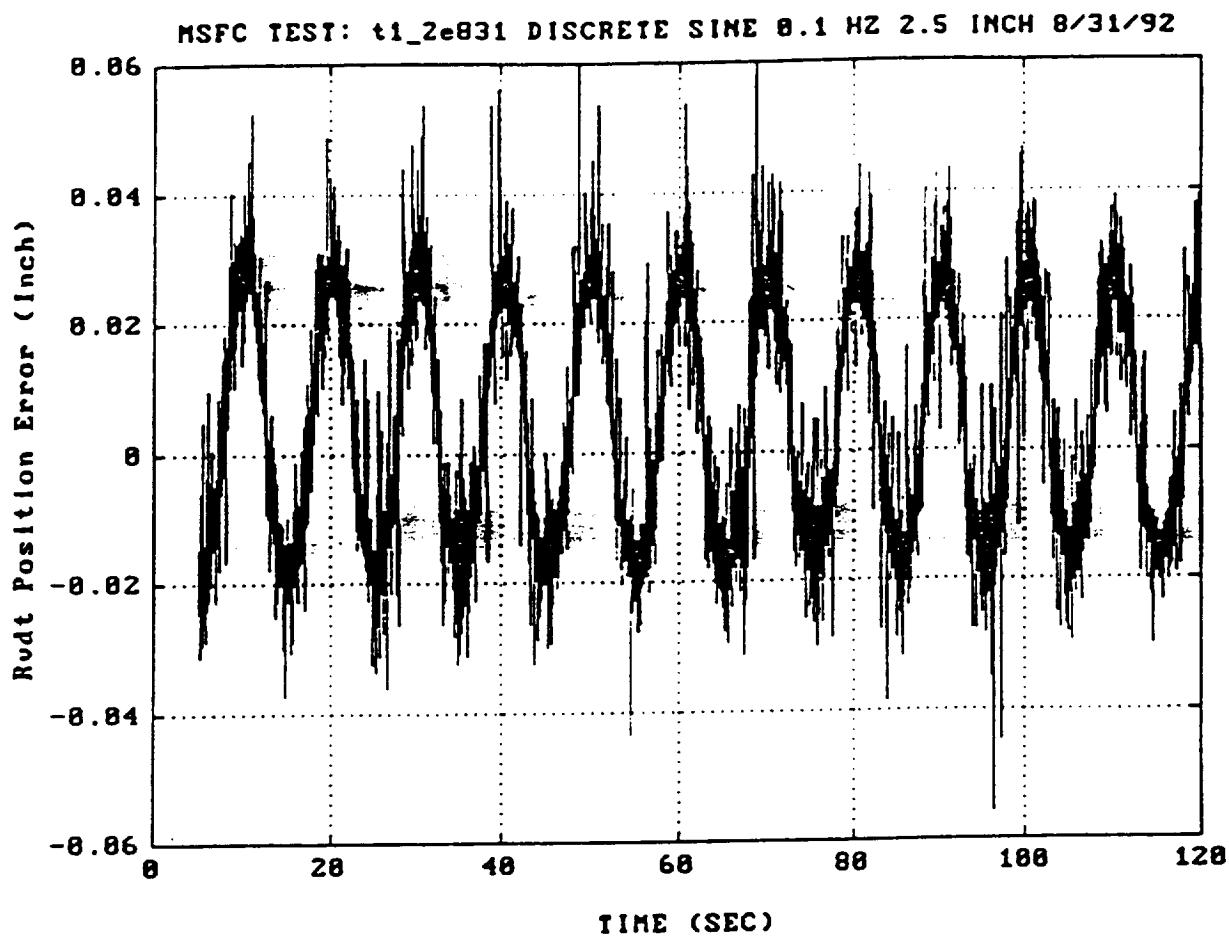


MSFC TEST: t1_2b831 DISCRETE SINE 0.1 HZ 0.1 INCH 8/31/92

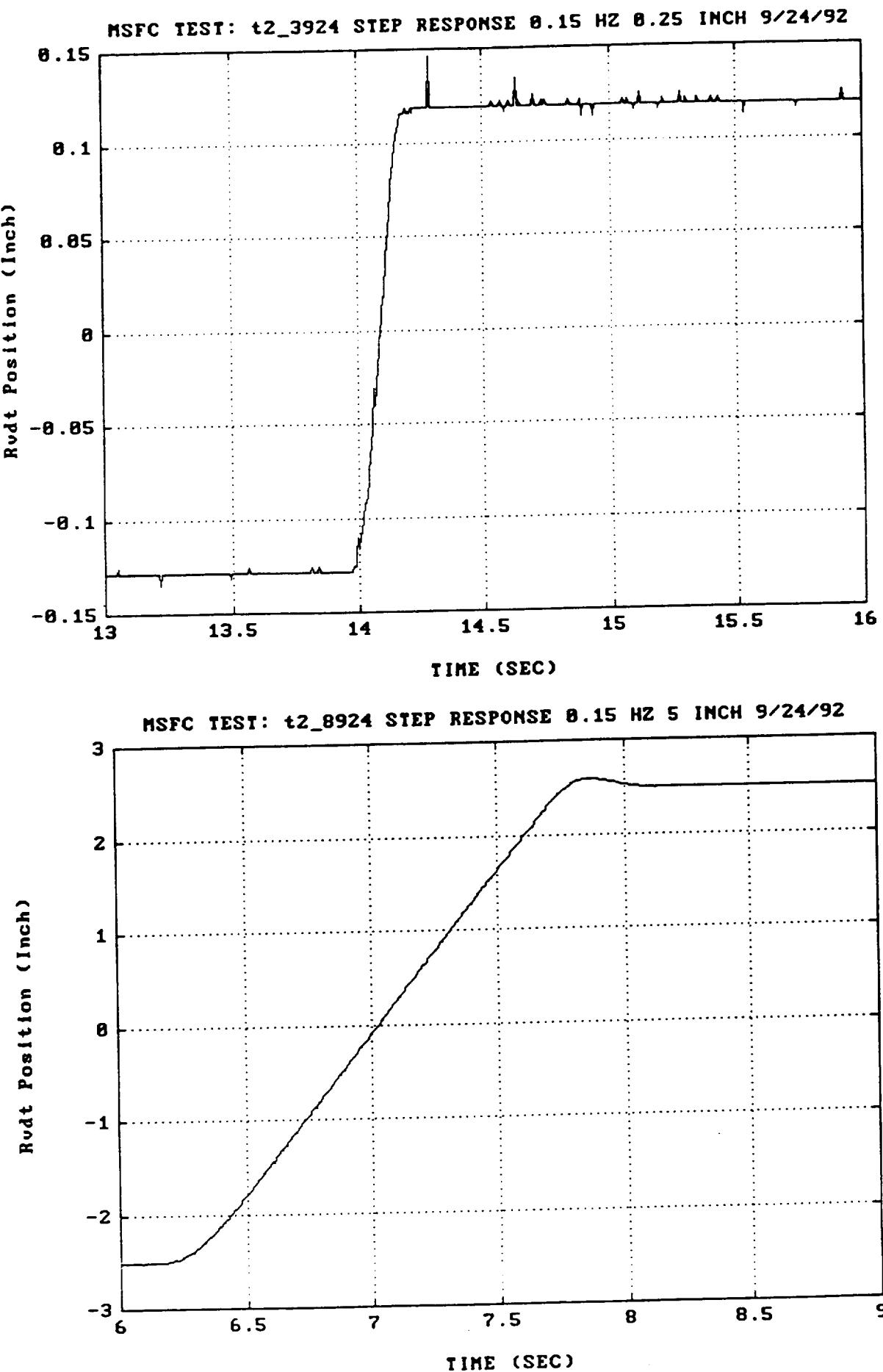


C-2

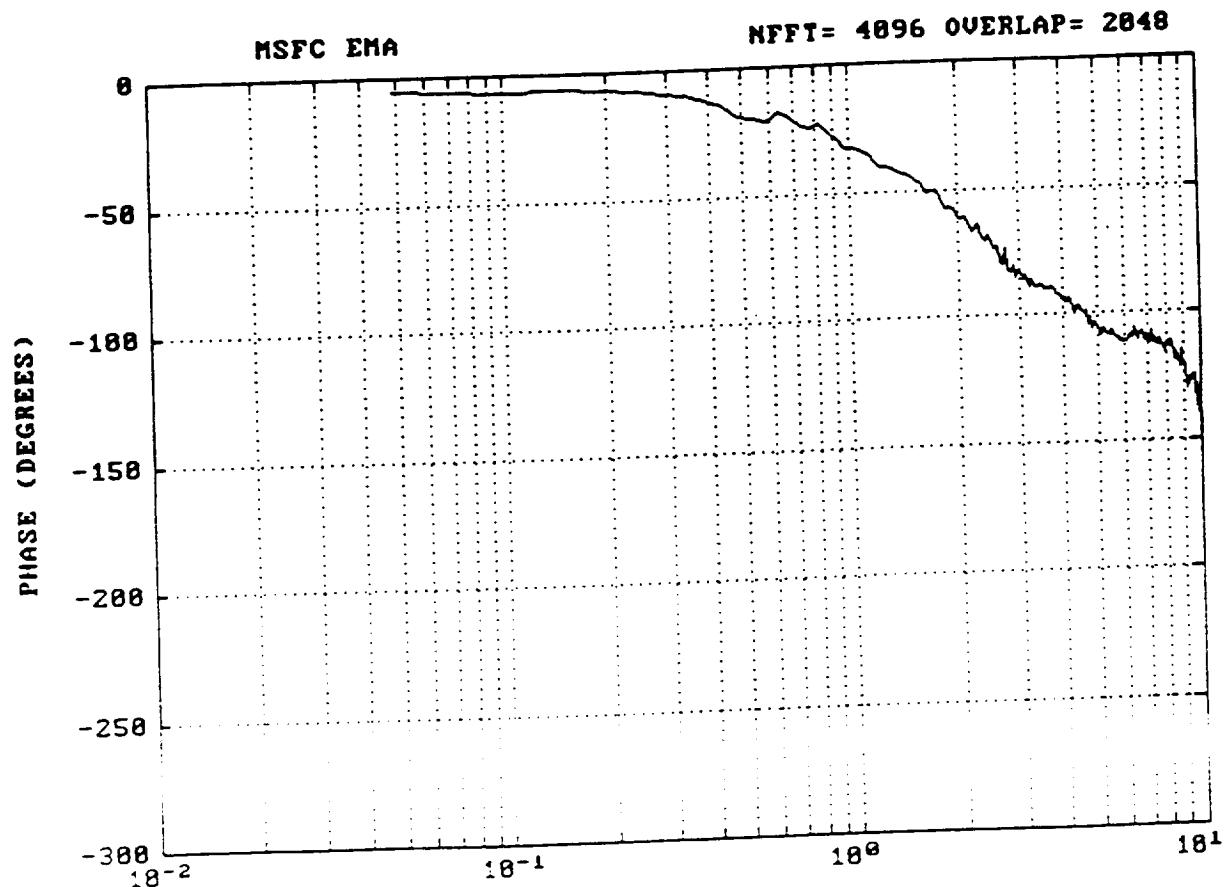
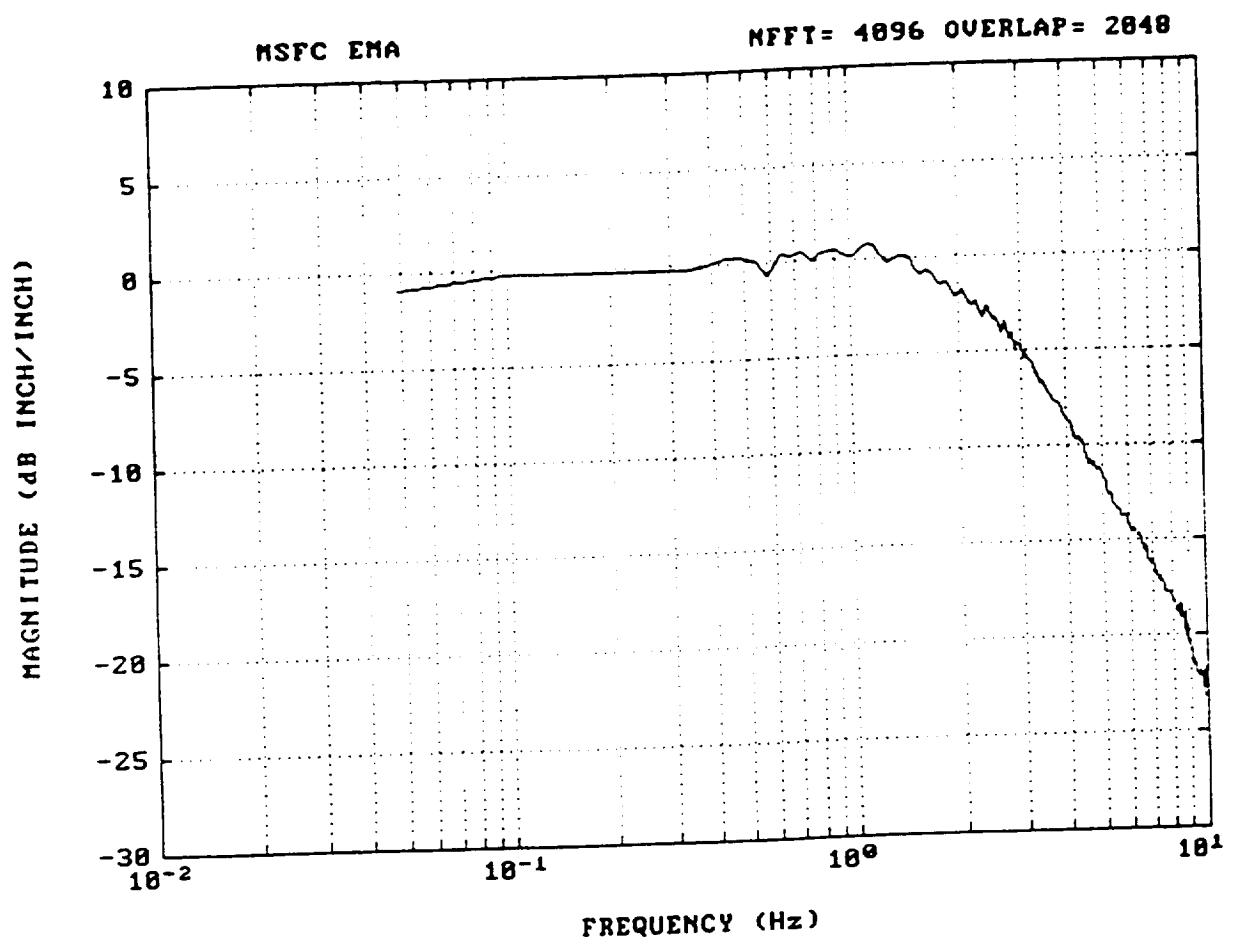
581



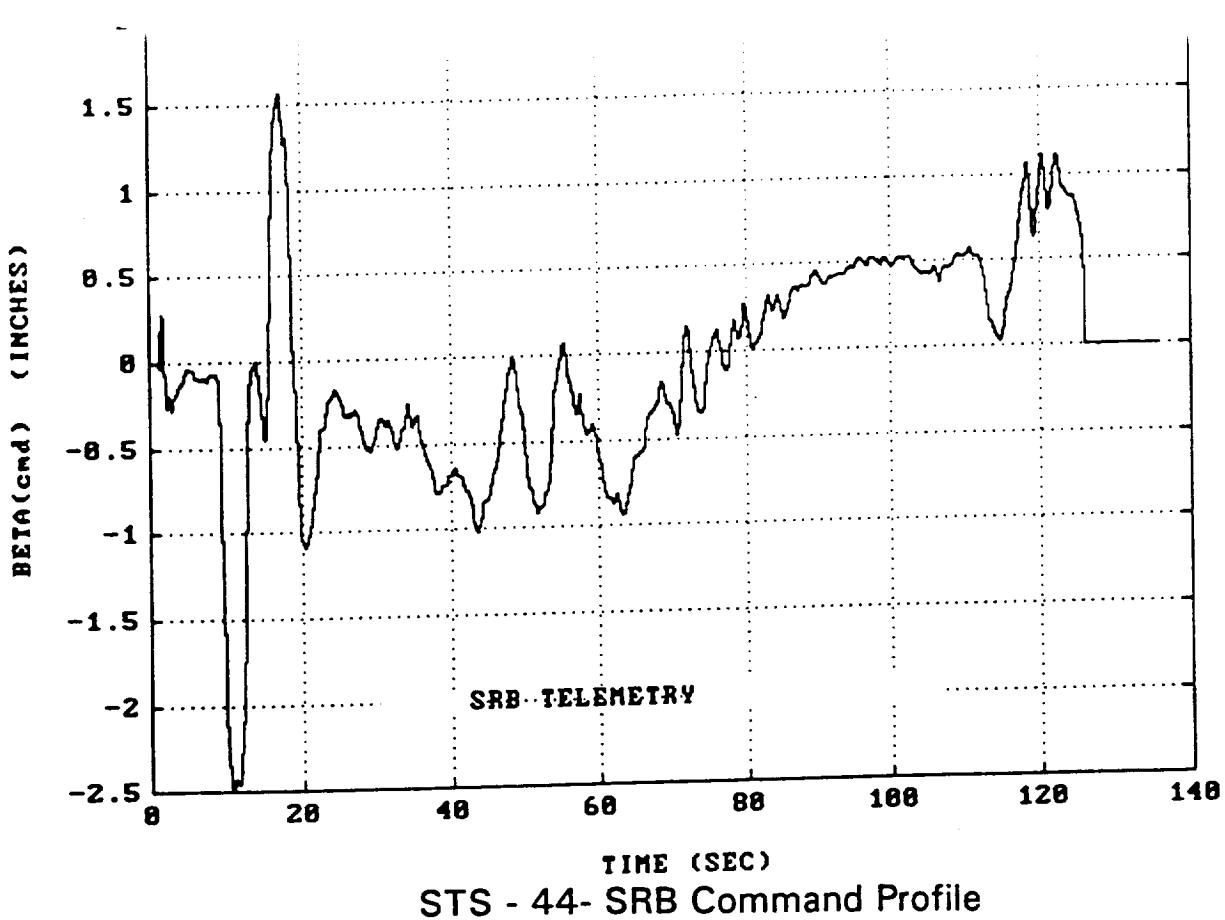
AFTER COMPLETION OF THE TEST PLAN ON THE INITIAL CONTROLLER CONFIGURATION, IT WAS DECIDED TO IMPLEMENT A RATE LOOP. PRELIMINARY RESULTS EFFECTIVELY REDUCE THE OVERTSHOOT BUT SHOW THE MAXIMUM RATE WAS REDUCED TO LESS THAN 4 IN/SEC AND ALSO A REDUCTION IN BANDWIDTH. THE NEXT STEP WILL BE TO TUNE THE RATE LOOP TO MEET ALL DESIRED SPECIFICATIONS.



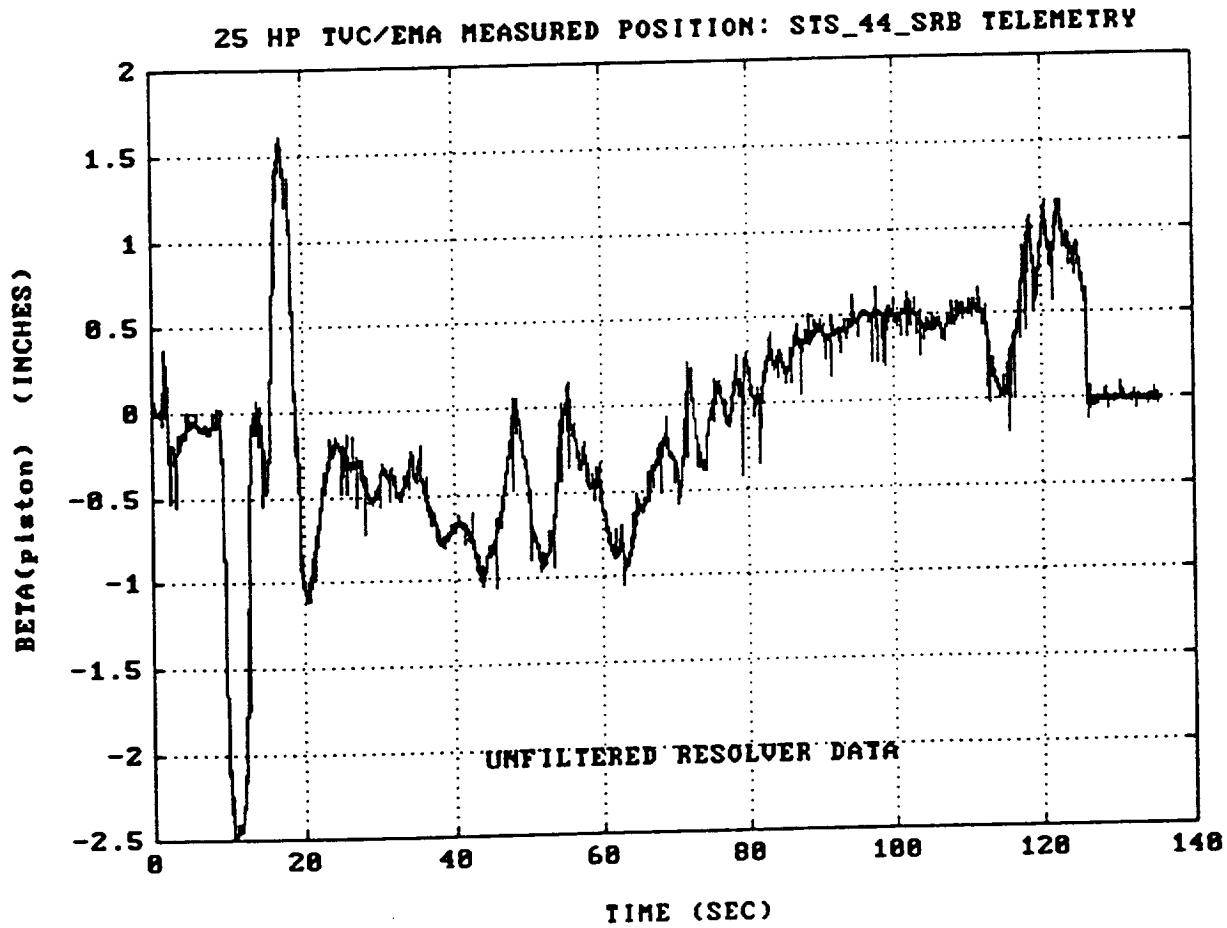
Step Response With Rate Loop



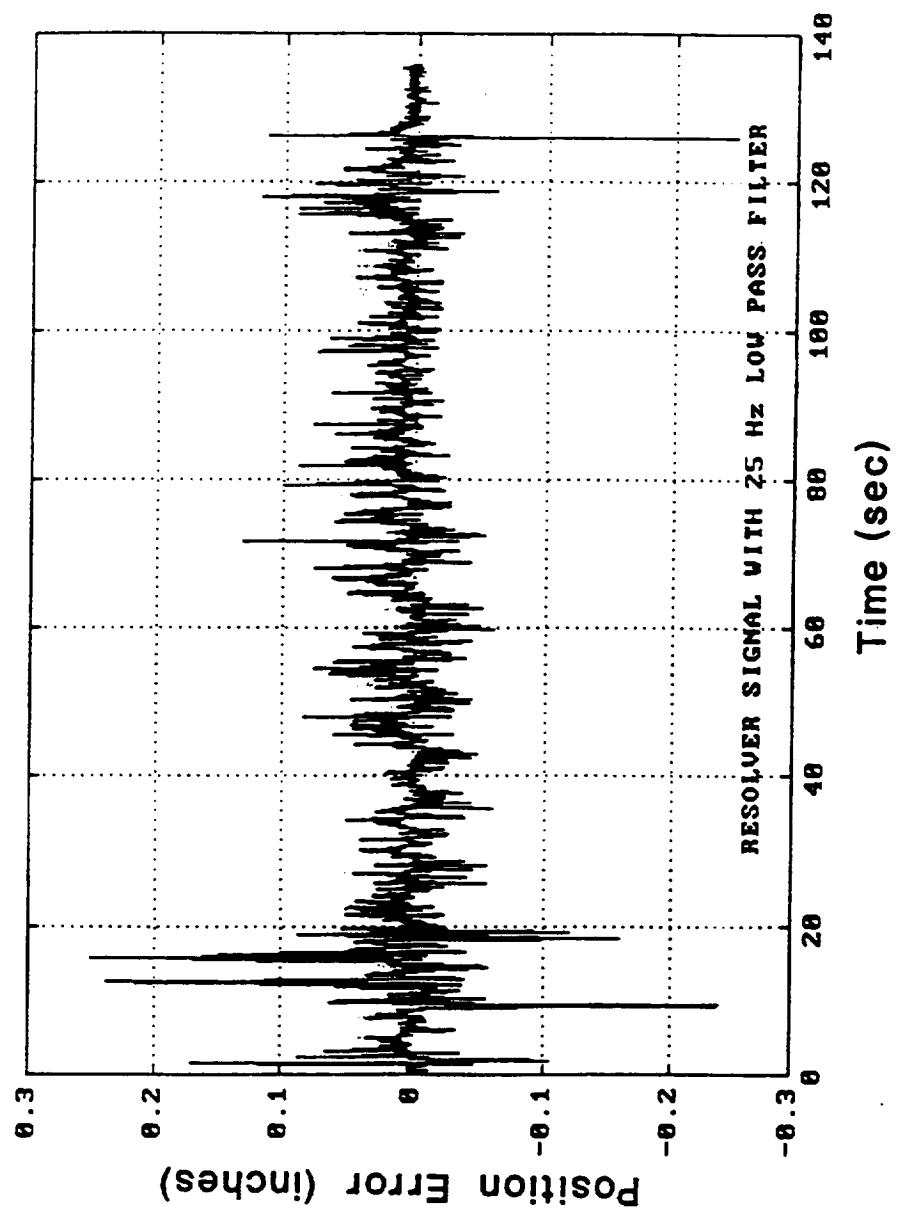
THIS VIEWGRAPH SHOWS THE STS-44 SRB COMMAND PROFILE AND THE TVC/EMA RESPONSE. THE NEXT VIEWGRAPH SHOWS THE POSITION ERROR BETWEEN COMMAND AND RESOLVER DATA FOR THE ACTUATOR. IN COMPARISON TO THE ACTUAL HYDRAULIC DATA, THE EMA ERROR IS SMALLER, ALTHOUGH FOR THE EMA SYSTEM NO FLIGHT TYPE LOADS (WIND GUSTS, ETC.) WERE APPLIED.



STS - 44- SRB Command Profile



PRELIMINARY 25 HP TVC/EMA RESPONSE TO STS-44-SRB COMMAND PROFILE



A NEW GEAR SYSTEM IS ON ORDER WHICH WILL ALLOW MSFC TO IMPLEMENT A TWO MOTOR CONFIGURATION ON THIS ACTUATOR. WHILE AWAITING DELIVERY OF THESE GEARS, THE RATE AND POSITION LOOPS OF THE CONTROLLER WILL BE TUNED TO MEET ALL DESIRED SPECIFICATIONS. TESTING WILL RESUME WITH DATA BEING USED TO VALIDATE THE ACTUATOR MODEL. THIS MODEL WILL BE USED FOR SIMULATION IN ADDITION TO TEST DATA TO DEFINE AND IMPLEMENT A REDUNDANCY MANAGEMENT SCHEME FOR THE TWO MOTOR ACTUATOR.

FUTURE PLANS

- Tune rate and position loops to meet desired specifications
- Demonstrate Rate vs Load capability
- Demonstrate Simulated Flight Load Capability
- Use test data to validate model
- Implement a two motor configuration
- Using model and test data, define and implement redundancy management scheme

**NATIONAL LAUNCH SYSTEM
TURBOALTERNATOR PSS
DEMONSTRATOR UNIT**

SEPT. 29, 1992

Allied-Signal Aerospace Company
AiResearch Los Angeles Division

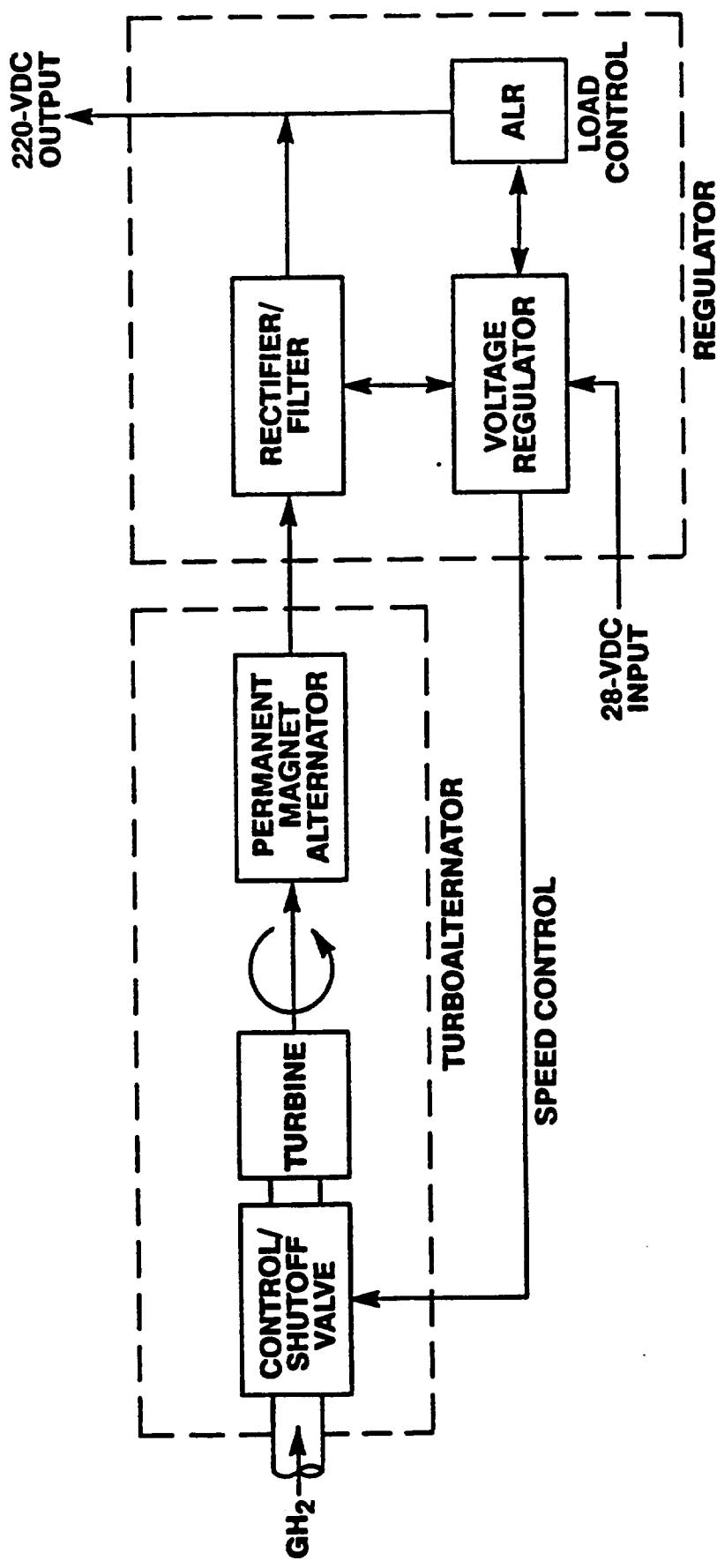


HIGH-SPEED, DIRECT-DRIVE TURBINE-DRIVEN PSS



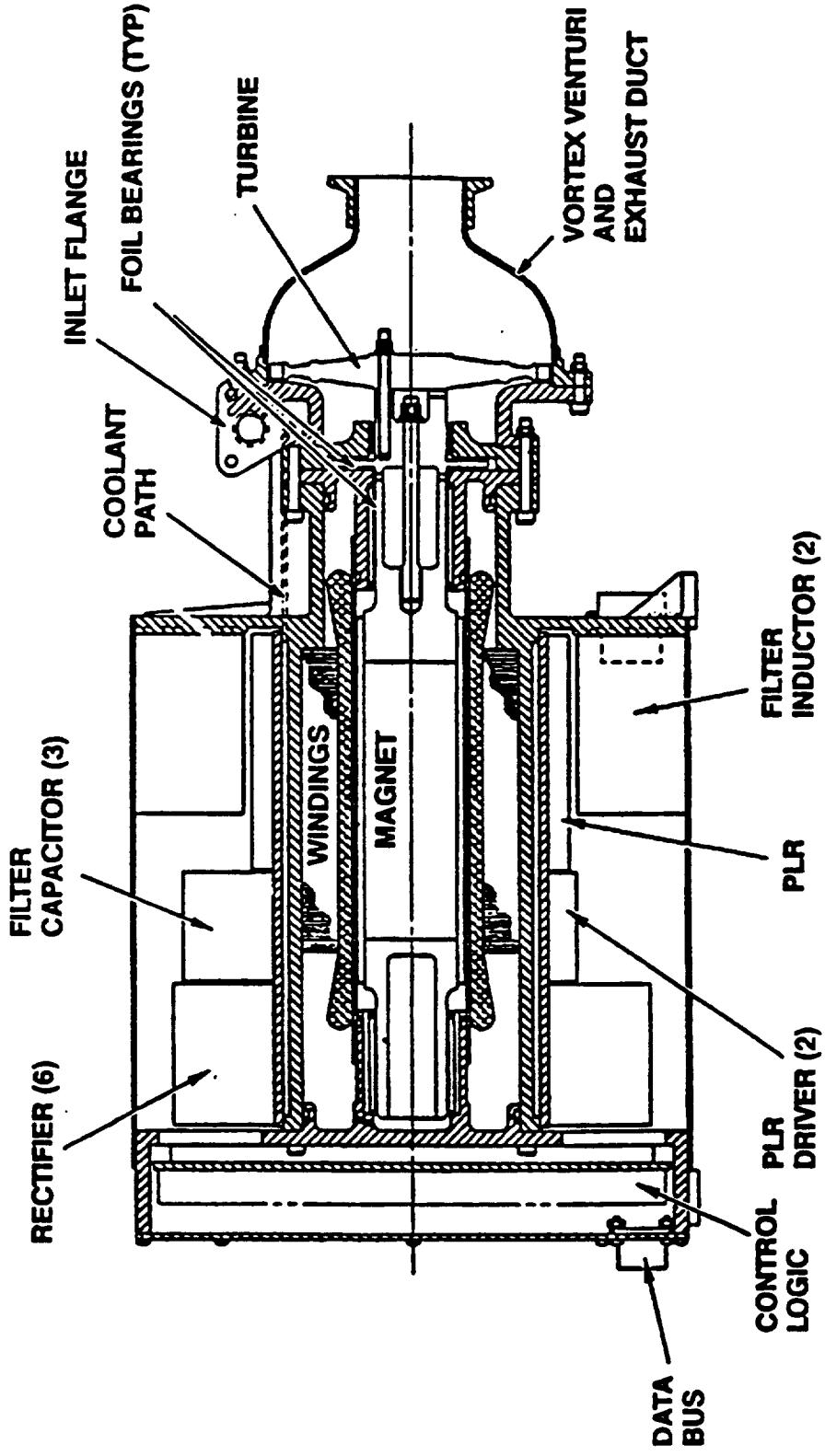
The basic components of the PSS are shown here along with how they interface with each other and the exterior load.

HIGH-SPEED PSS BLOCK DIAGRAM



This cross section of the hydrogen powered PSS turboalternator shows the single two pole toothless alternator rotor directly driven by the single stage axial impulse turbine. A vortex venturi provides passive overspeed protection. Also shown are the radial and the axial foil bearings. The electrical power conditioning and speed control electronics are installed around the periphery of the turboalternator. All cooling is provided by the gaseous hydrogen.

HIGH-SPEED PERMANENT-MAGNET ALTERNATOR PSS CROSS SECTION



IG-1118-A

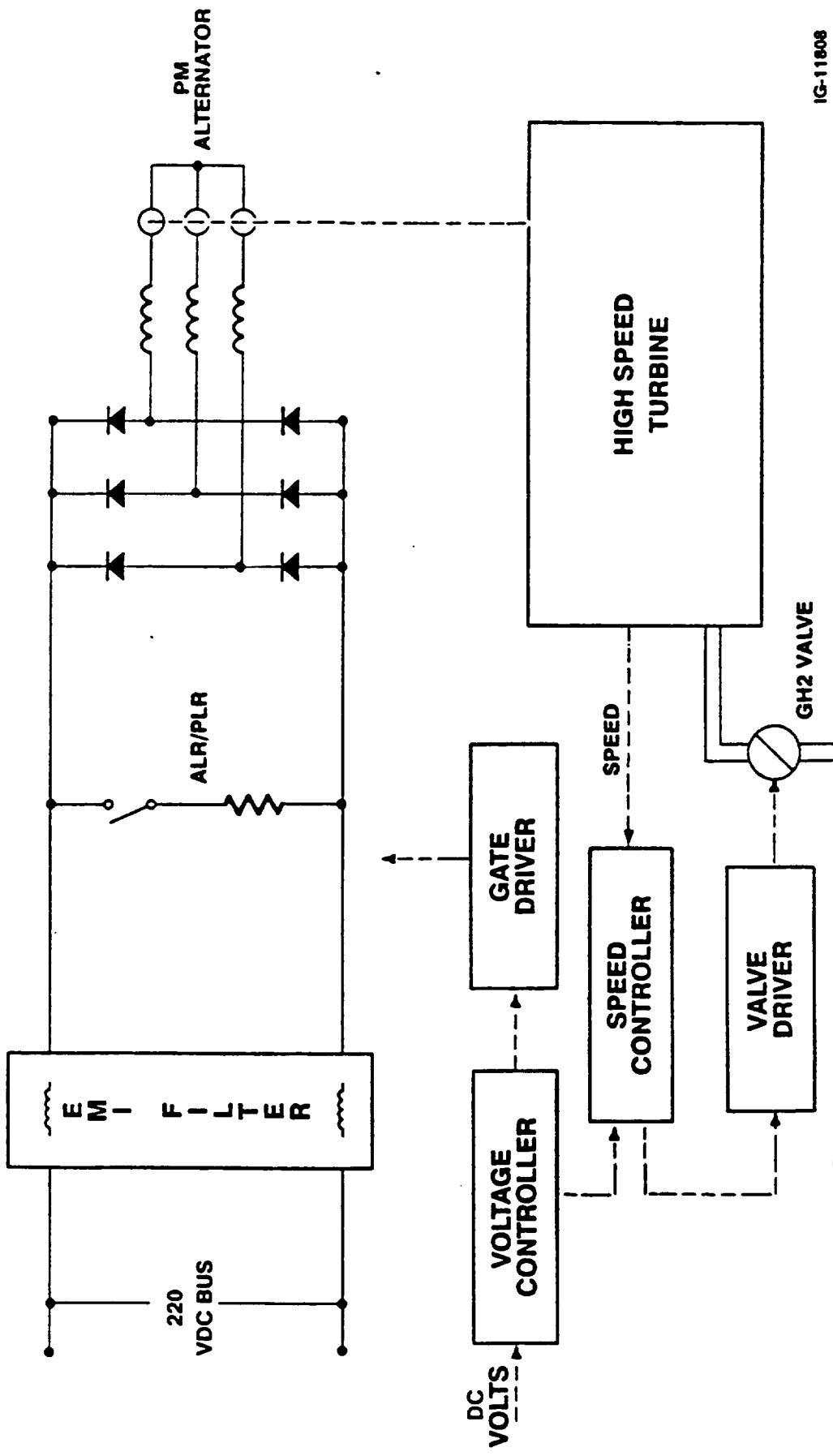
Allied-Signal Aerospace Company

AIR Research Los Angeles Division

Allied Signal

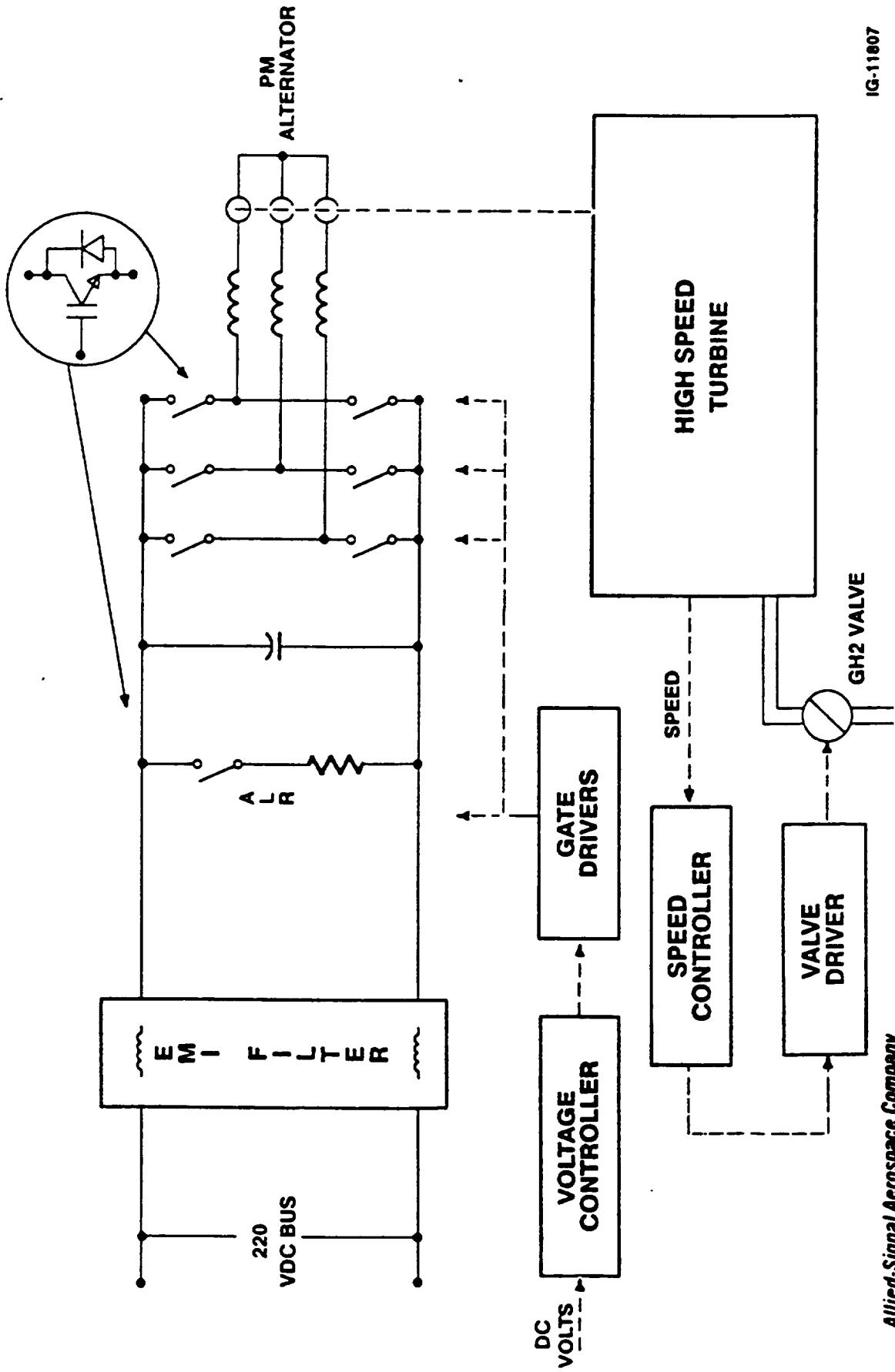
This schematic shows the simple rectifier design power conditioner. The output voltage level is a function of the electrical load and the rpm.

HIGH SPEED PSS WITH RECTIFIER



This alternate inverter-type power conditioner is less dependent on rpm. The inverter operates in an upchopping mode, eliminating voltage droop due to speed and load changes.

HIGH SPEED PSS WITH INVERTER



Allied-Signal Aerospace Company

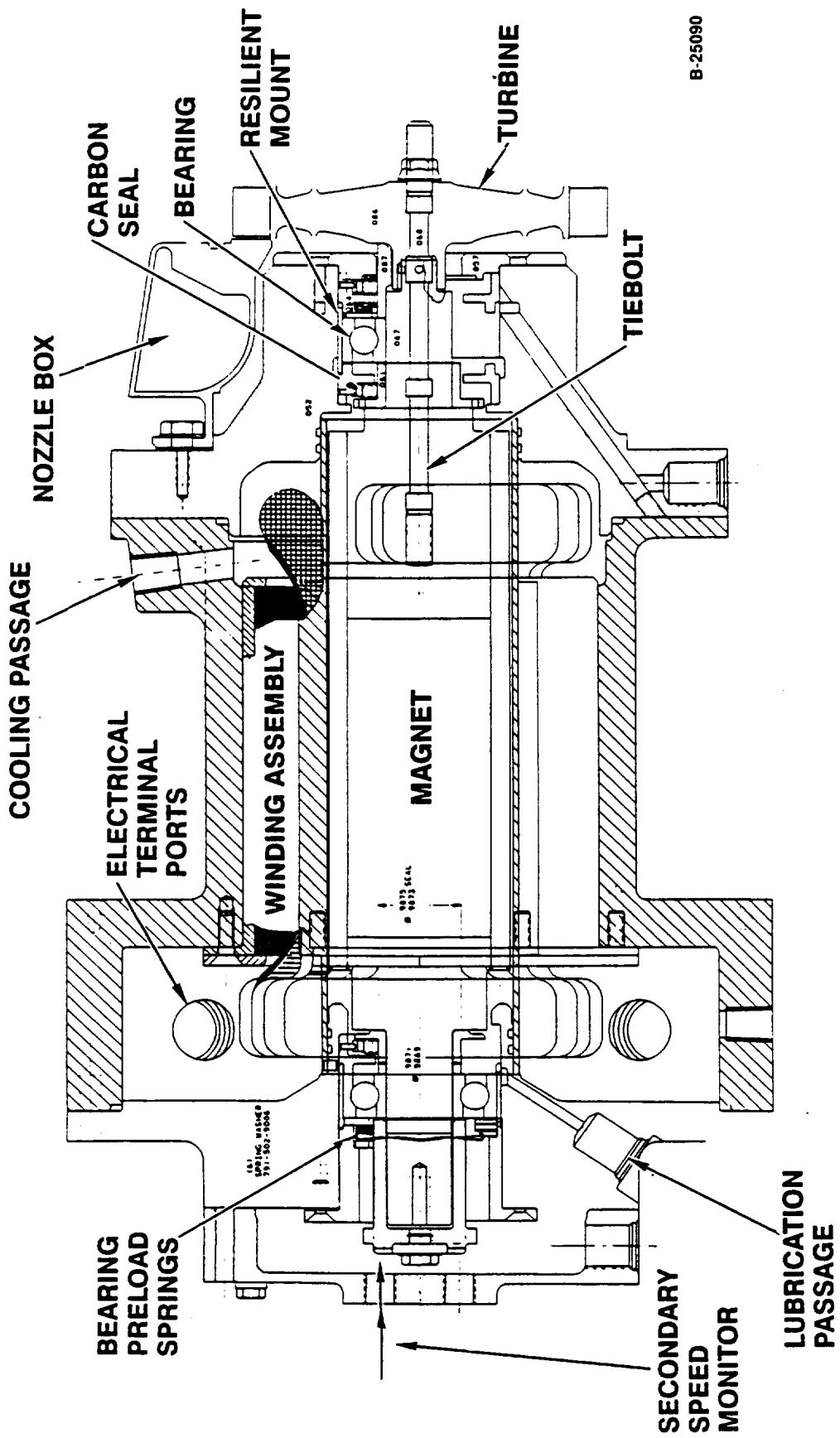
AirResearch Los Angeles Division

IG-11607



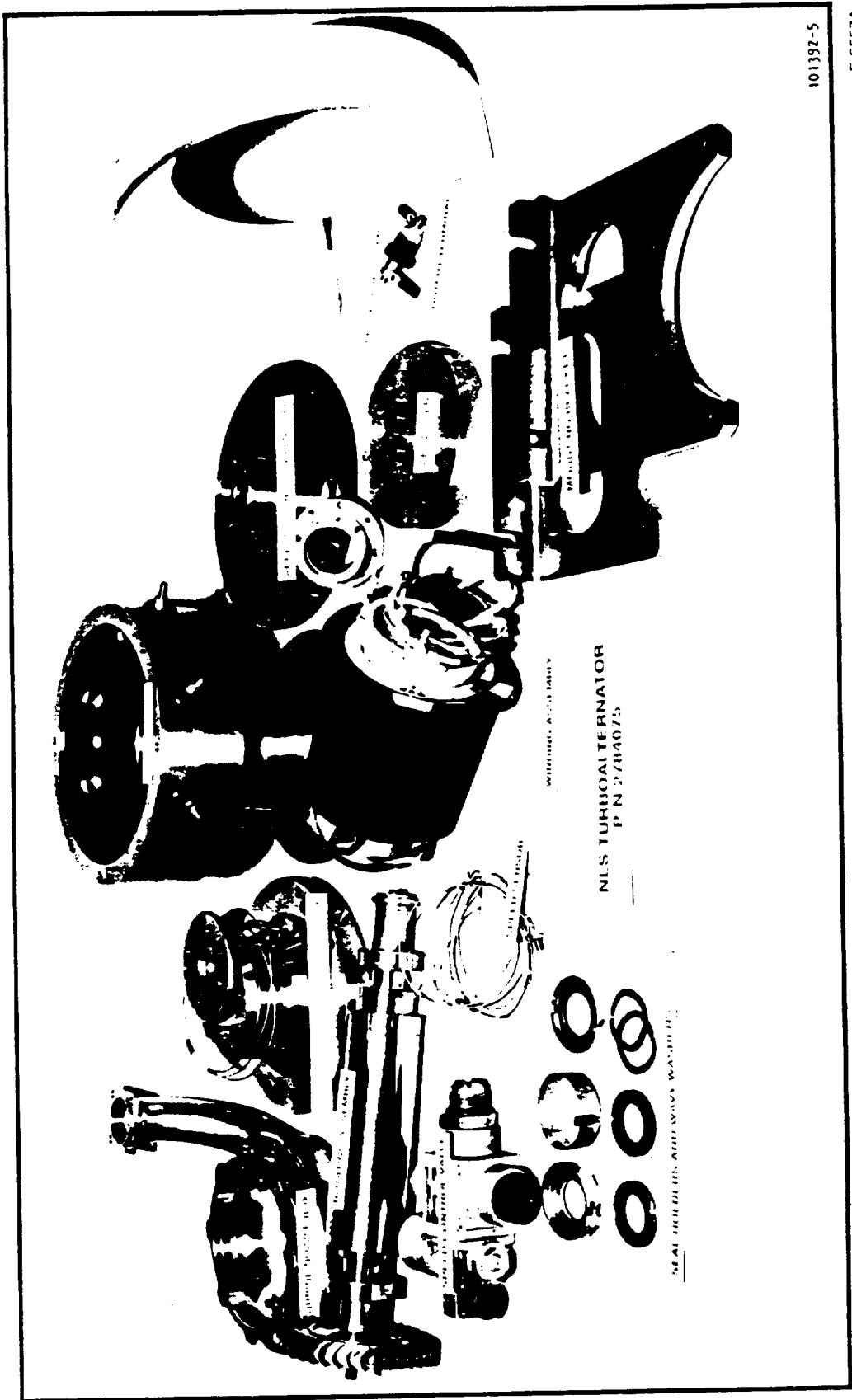
This is a cross-section of the helium powered turboalternator demonstration unit. It consists of heavy hogged out structures and utilizes oil mist lubricated angular contact ball bearings. The arrangement of the turboalternator components is similar to that of the hydrogen demonstrator unit.

NLS PSS TURBOALTERNATOR



**Pictured are the details and subassemblies which make up the
PSS helium demonstrator turboalternator.**

NLS TURBOALTERNATOR
P/N 2784075



101392-5

F-65574

NLS TURBOALTERNATOR
P/N 2784075

MADE IN U.S.A. AND SWEDEN

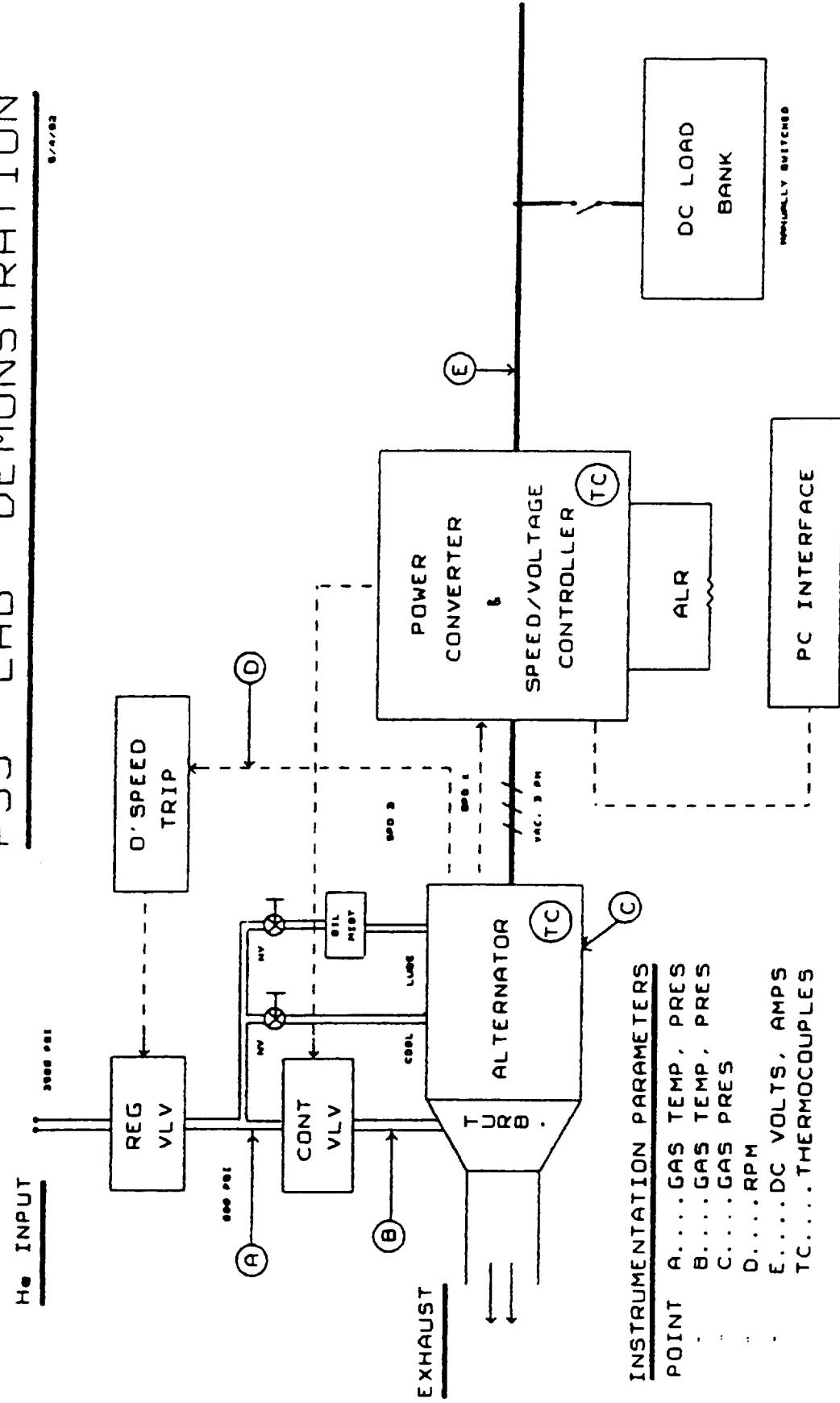
Allied-Signal Aerospace Company

AiResearch Los Angeles Division



This is the schematic of the PSS setup for the development and demonstration tests. The power converter can be operated in either the rectifier or inverter (upchopper) mode.

PSS LAB DEMONSTRATION

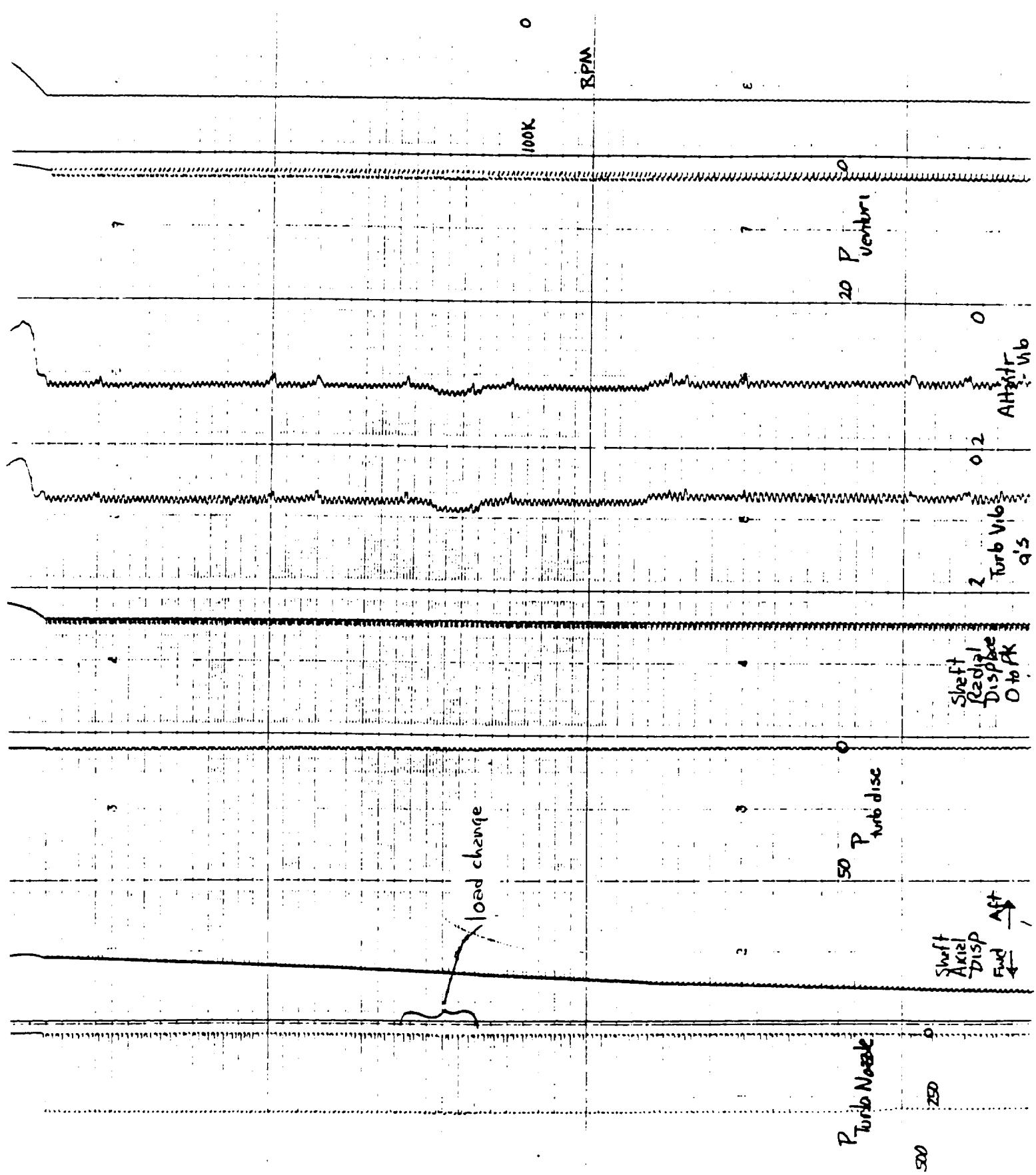


**The majority of these tests have been accomplished. Application
and shedding of the maximum electrical load as a step function
under various conditions is not yet complete.**

GIHe TEST PLAN OVERVIEW

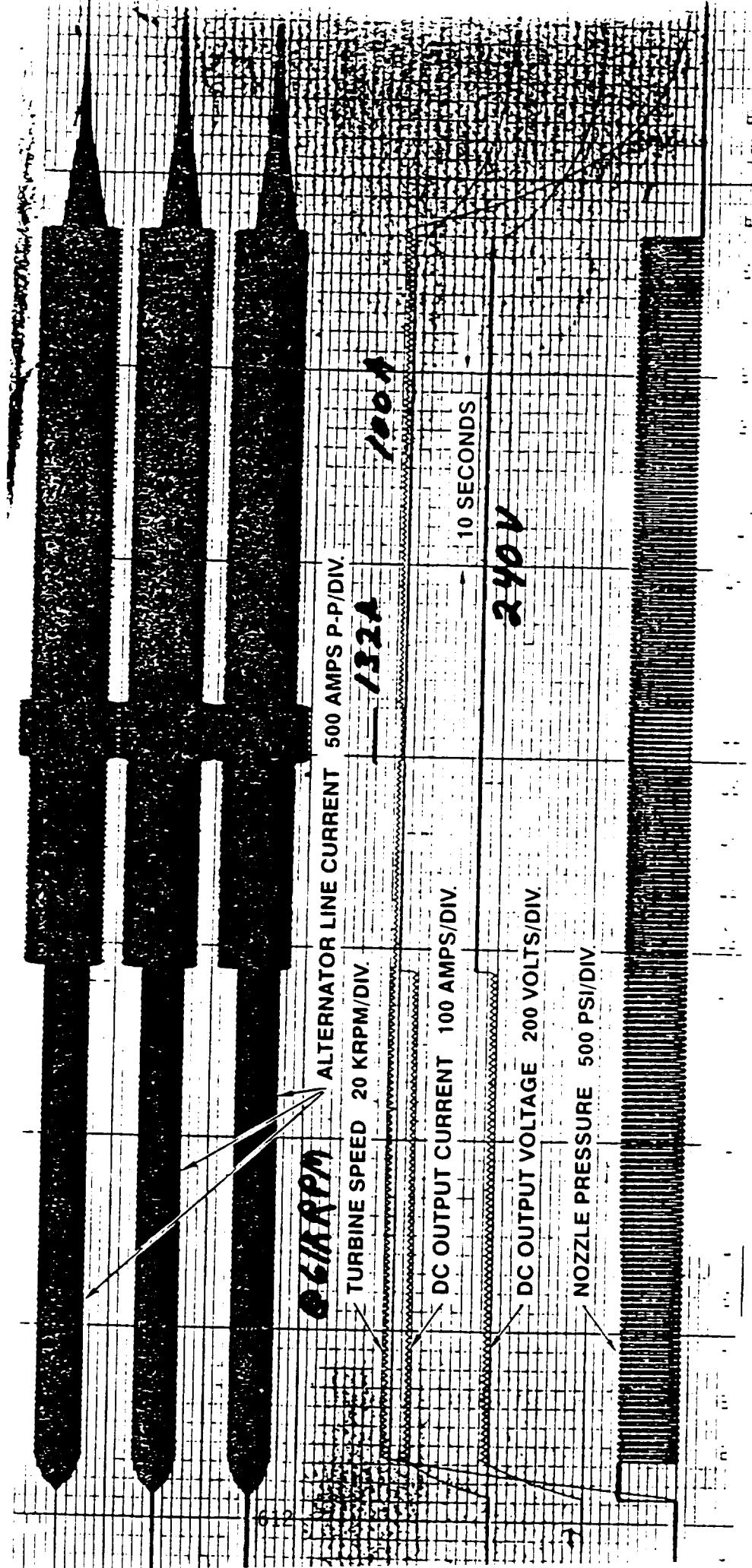
- VIBRATION SURVEYS
- VORTEX VENTURI EFFECTIVENESS
- TURBINE PERFORMANCE
- WINDING RESISTANCE AND INDUCTANCE
- NO LOAD VOLTAGES
- SPINDOWN TESTING
- STEADY STATE LOADS
- TRANSIENT LOADS
- LOAD REGULATION
- OPERATING AND SOAKBACK TEMPERATURES
- PRESSURE DIFFERENTIALS

Shown here are the traces of rpm and helium pressure to the turbine as the turboalternator; was started up under load, was run in the rectifier mode, accomplished an output voltage (and current) increase by switching to the upchopper mode, had additional partial load applied and shed as step changes, and was shut down.



This is another stripchart recording of the test described on the previous page. It shows traces of the currents, DC output voltage, rpm and turbine nozzle pressure. The output voltage is closely regulated during the load changes.

BOEING/ALLIED-SIGNAL
GHe 2 TURBO ALTERNATOR



The major similarities and differences between the helium and hydrogen powered PSS demonstrator units are shown.

PSS TURBOALTERNATOR DESIGN COMPARISONS

	<u>Helium Demonstrator</u>	<u>Hydrogen Demonstrator</u>
Power Output	35 kw at 220 vdc	35 kw at 220 vdc
RPM	65,000	60,000
Voltage Control	Rectifier & Upchopper	Rectifier or Upchopper
Speed Control Valve	Limit Cycling	Proportional
Bearings	Ball/Oil Mist	Foil/GH ₂
Weight	180 lbs.	75 lbs.
Packaging	Two Separate Components	Wrap-Around Electronics

**THE CAPABILITY TO DEVELOP THE REQUIRED 35 KW ELECTRICAL
POWER HAS BEEN DEMONSTRATED**

Allied-Signal Aerospace Company

AirResearch Los Angeles Division



SESSION IX

ELA HARDWARE DEMONSTRATIONS & PAPERS

ITW Spiroid
An Illinois Tool Works Company
2801 North Kester Avenue
Chicago, Illinois 60638
Telephone 312.227.2200
FAX 312.227.0535

ITW Spiroid

ITW SPIROID

ITW Spiroid, A Division of Illinois Tool Works, is a manufacturer of proprietary, custom gear forms, roller screws, and index rings. These products come in the form of Spiroid + Helicon right angle gearing, Concurve spur gears, Spiracon roller screws, and Endicon index rings.

ITW Spiroid provides their products for a large number of diverse applications. Approximately 50% of our volume goes to both military and commercial markets. Military applications include such equipment as the Apache Helicopter, M109 Howitzer, F15 Fighter Aircraft, and the Harpoon and RAM Missiles. Commercial applications include Hand Tools, Laser Imaging Devices, Machine Tool + Fixturing Devices, Tundish Car Actuators, and Aircraft Flap Actuators.

Spiroid/Helicon - Right Angle Gearing

Spiroid	Helicon
10:1 - 400:1	4:1 - 400:1
High Contact Ratio	High Contact Ratio
Higher Capacity	High Capacity
Good Efficiency	Better Efficiency

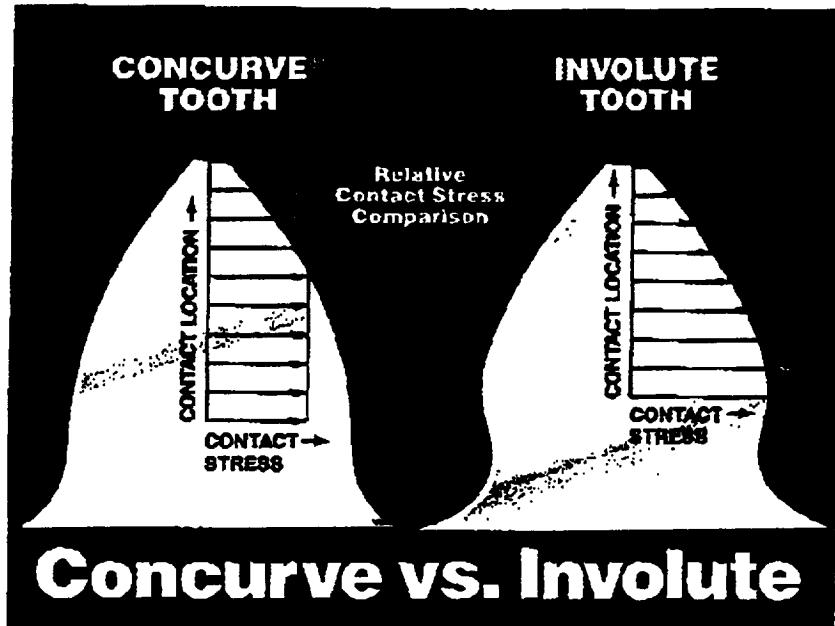
Possible Cross Shaft Design
Backlash Control
Material Variability

These gear forms have the widest center distance of any right angle, face type gear form thereby producing the highest contact ratios possible. This allows for high capacity in small space envelopes thus affecting packaging, weight, and power density.

Concurve Spur Tooth Gears

This gear form is a variation of an involute spur tooth form where the tooth profile has a relatively constant radius of curvature from the tip of the tooth to the root of the tooth. This distributes the contact stress evenly up + down the tooth flank. Involute spur gear teeth tend to have ever increasing contact stress as you move from tip to root of the tooth.

- 2 -



The even distribution of stress in Concurve gears allows for higher loads and lower numbers of pinion teeth due to this feature. Therefore, pinions with as few as 4 teeth and ratios up into the 20's:1 are possible. Removal of gear passes, higher loads, higher ratios and downsizing are all possible.

Spiracon Roller Screws

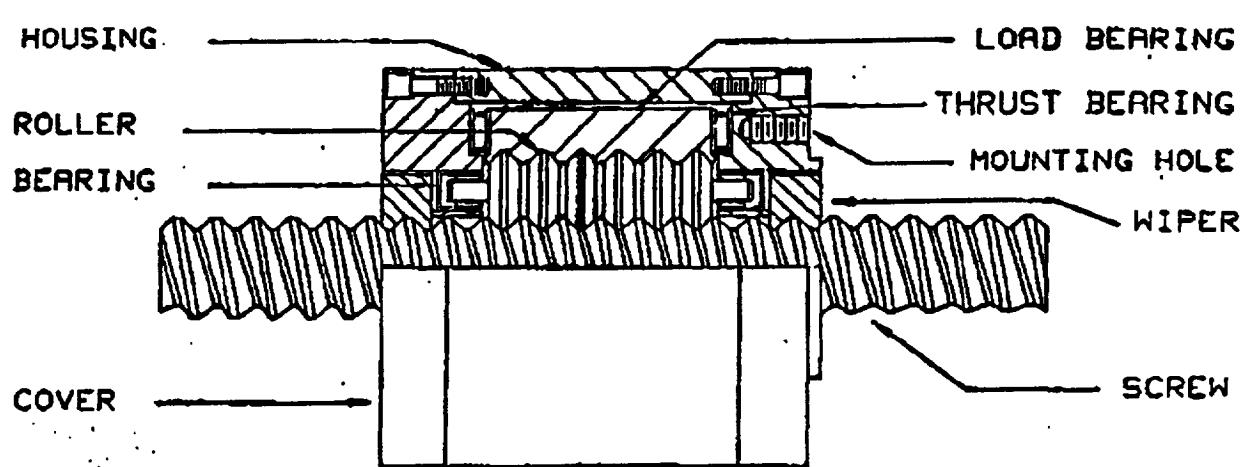
Spiracon Roller Screws offer several advantages over Ball Screws and Acme Screws. The basis for these advantages lie in a discussion of the type of contact that exists between members within the nut itself.

Acme Screws have line contact between members. They have great capacity for this reason. However, there is so much contact and with the elements sliding upon each other, the efficiency is extremely low, usually around 20%. Thus motors tend to be very large to overcome this inefficiency.

Ball screws have point type contact between members. Imagine a ball riding in a trough of slightly larger curvature. A small point exists between these two members upon which the load will be carried. For this reason they have limited capacity. However, due to this small contact area and the rotation of all internal components, ball screws are generally very efficient.

- 3 -

Spiracon Roller Screws have line type contact between members. These lines create a large area over which the load is carried thus decreasing the stresses on the components. Higher capacities, longer life and reduced size are all possible. All internal components do rotate however, because of the increase in contact area, roller screws are slightly less efficient than ball screws.



SPIRACON® ROLLER SCREW

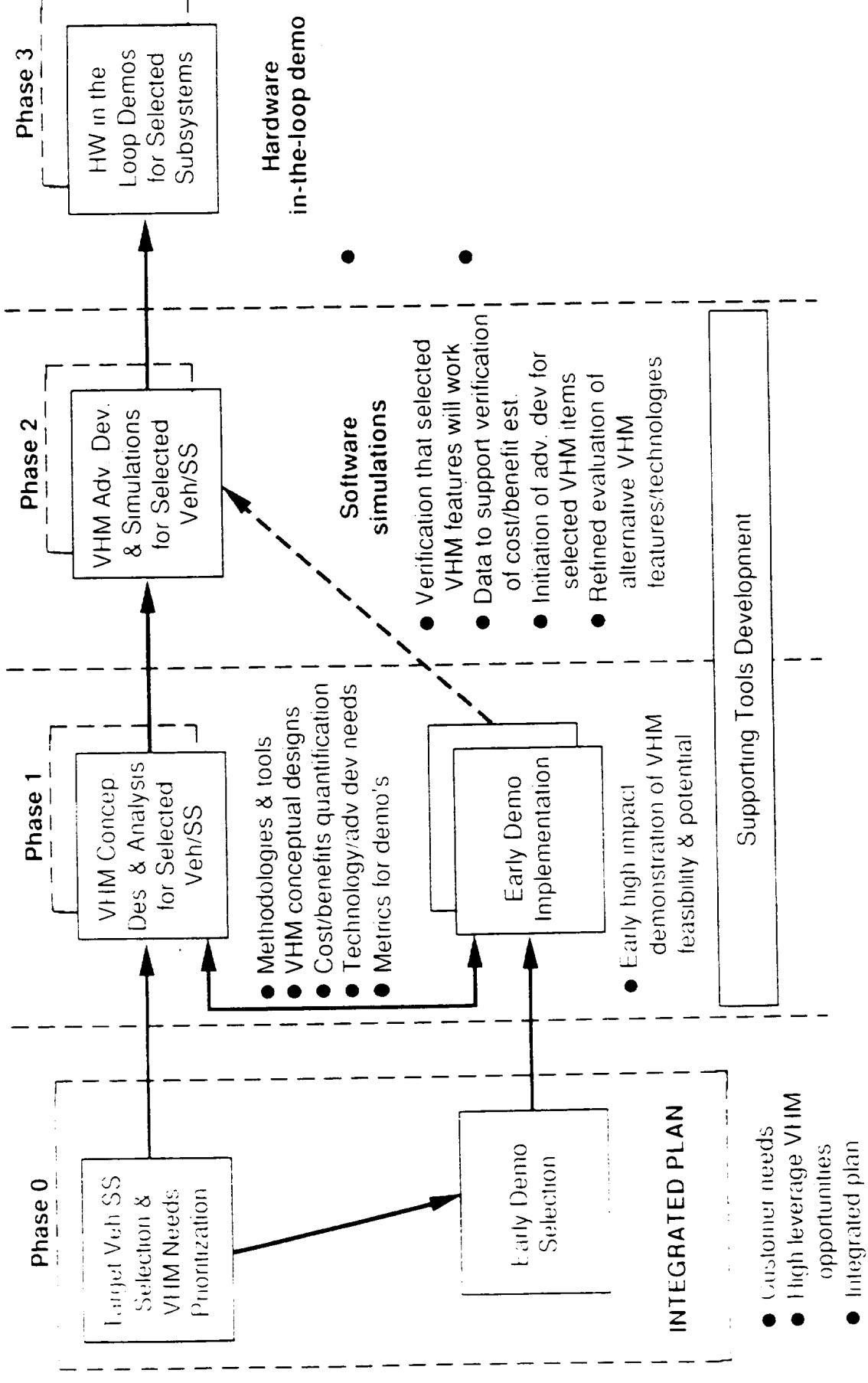
Endicon Index Rings

Endicon Index Rings consist of 2 mirror image gear halves with teeth machined such that intimate contact exists between the two halves. They can be used as indexing devices, couplings, centering devices, etc. They have been used previously in such applications as Indexing Tables, Multi-Stage Turbine Blade Alignment devices, Robotic end effector joints and Blind Assembly Robotic couplings.

SESSION X

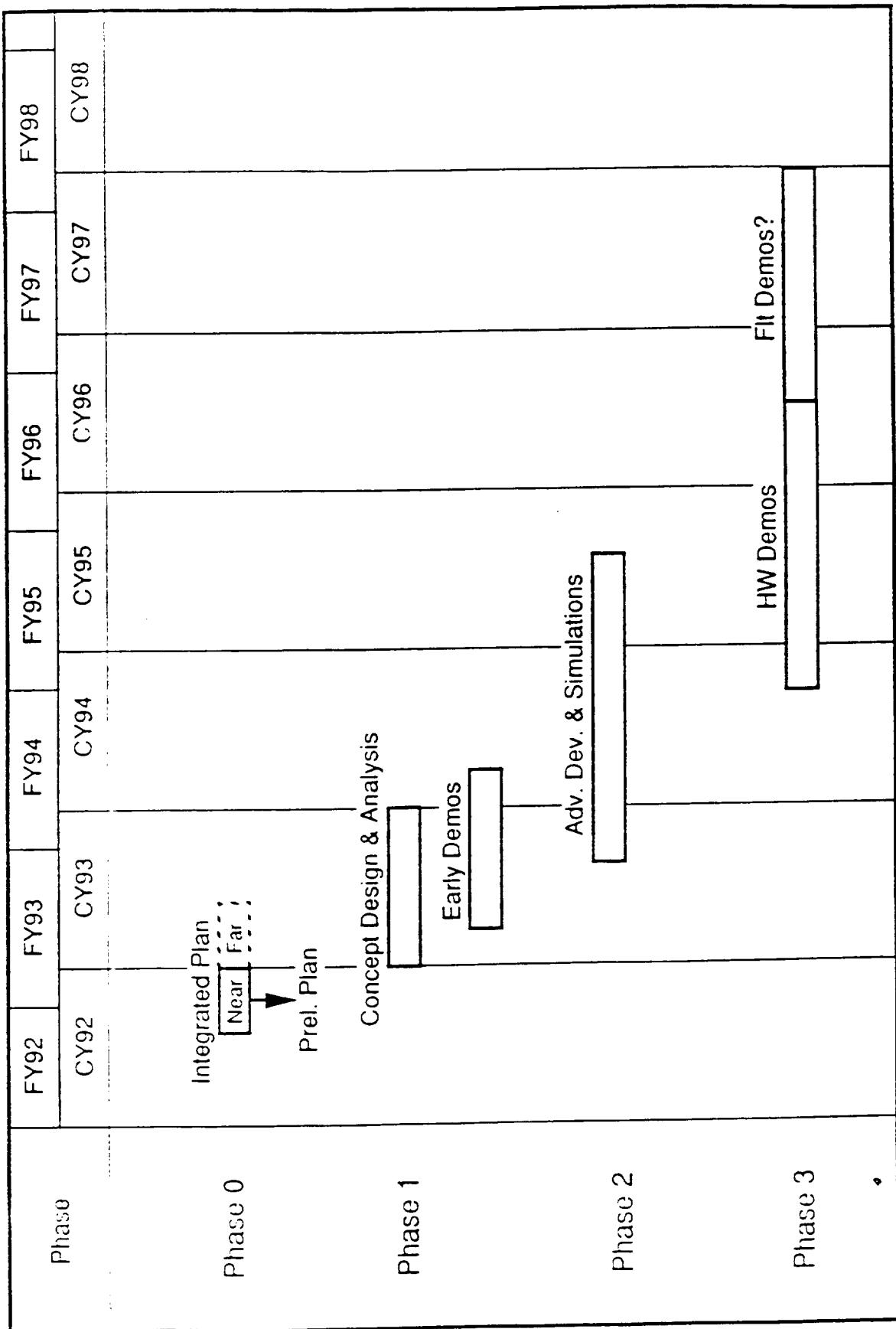
EMA FDIR AND VHM

IVHM ADVANCED DEVELOPMENT PROGRAM



VHM Development Plan

Schedule





TASK PRIORITY PHASE 0

<u>TOP PRIORITY</u>	<u>TARGETS SUPPORTED</u>
Real time engine diagnostics	ELV, STS
Leak detection	ELV, STS
IVHM Architecture	ELV, STS
Ground processing Integration	STS
IVHM for EMA	ELV, STS
OMS/RCS	STS
IVHM Cost/Payback analysis*	STS
<u>DESIRABLE</u>	
Post flight/test data analysis for engines	
IVHM for mission operations	
Automated Inspection techniques for engines	
Flight/ground test plume spectroscopy	
Laser pyros	
SSF Fault Management system	
Hybrid Reliability/fault tolerance/cost tool	
Application required for all demos	

EMA Health Management Using Smart Sensors

**NASA Electrical Actuation Technology
Workshop**

Honeywell Systems & Research Center

Jeff Schoess

1 October 1992

EMA Health Management Agenda

- Role of Health Management -- A Honeywell Perspective
- Launch Vehicle Management Approach
 - * NLS Avionics Configuration
 - * Vehicle Integration Logic Flow
 - * Functionality Definition
- Key Building Block Technology --- Smart Sensors
- Recent Technical Progress
 - * 2 HP EMA Motor Current Health Monitoring
 - * 28 HP EMA Test Evaluation
- Smart Structures Technology --- Launch Vehicle Application
- Summary

Systems and Research Center

Mission: *Applied research for Honeywell's space and aviation business*

Minneapolis



Phoenix



Bloomington



Resources

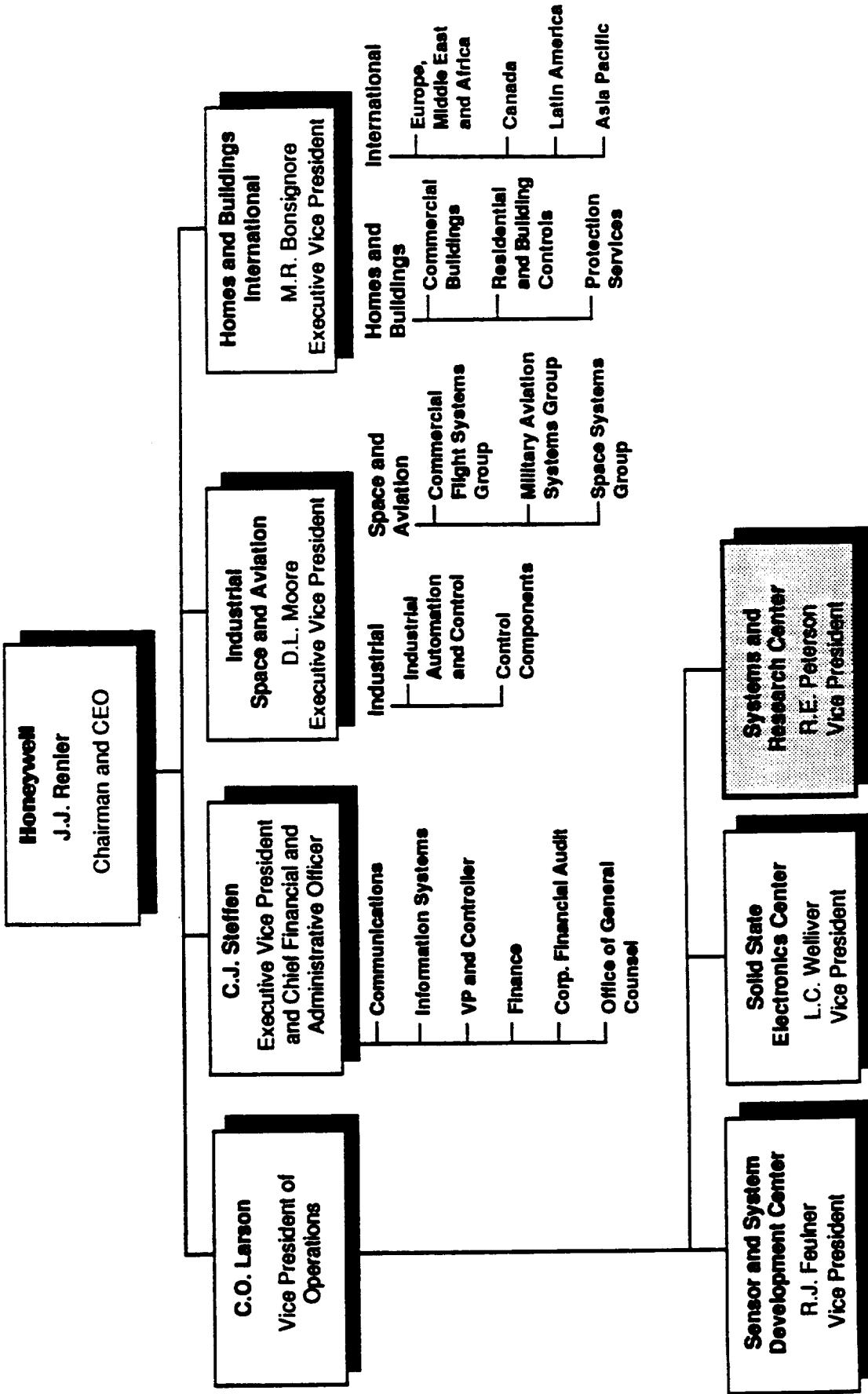
460 people	\$45M Total Funding
280 engineers/ scientists/ technicians	\$32M Contracts \$ 9M R&D \$ 4M Divisions

Technologies

Sensors	Control Systems
Microsystems/Circuits	Displays
Signal Processing	Computer Systems

Honeywell

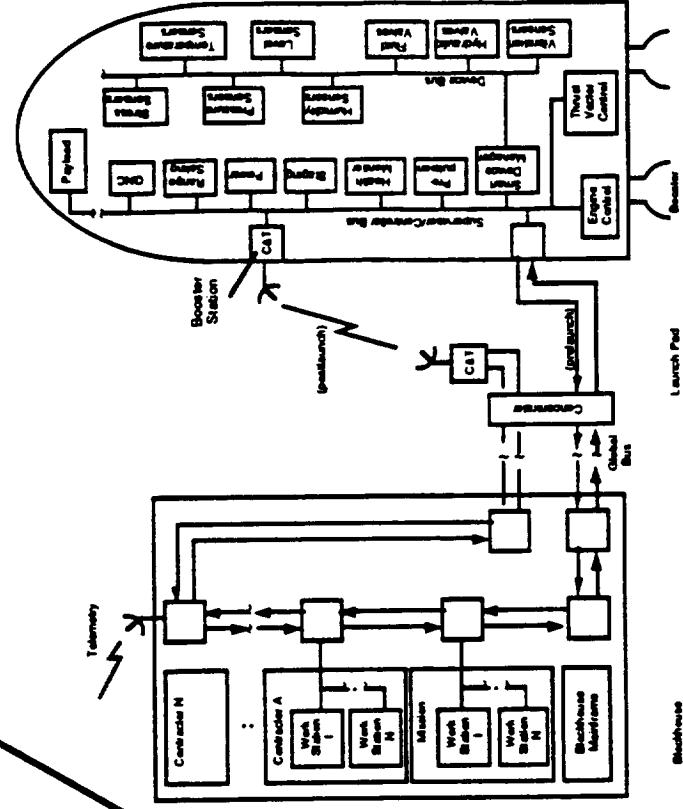
Honeywell Inc.



Health Management Philosophy

Human

Health management is more than not being sick—it's a way of life aimed at reducing your risk of serious illness

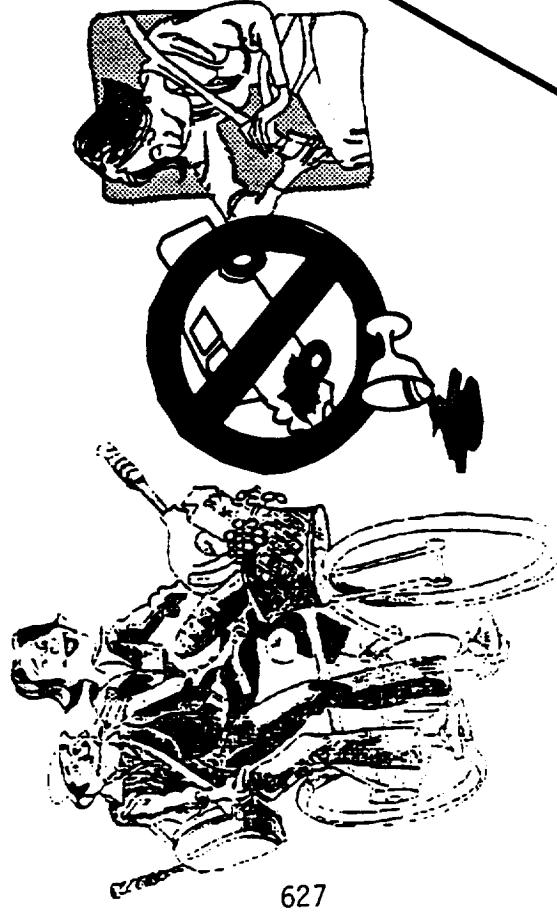


Launch System

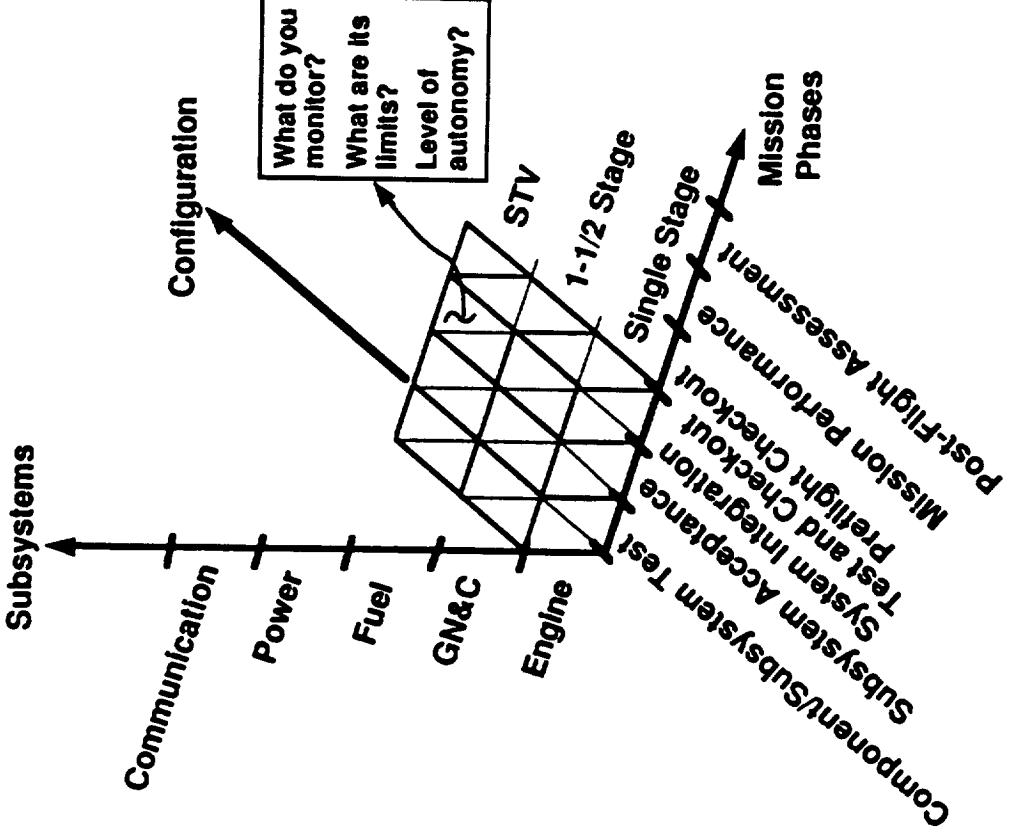
Health management is more than determining that a system is working nominally—it's a system design aimed at reducing the risk of system- and mission-threatening failures

Honeywell

C010511-51



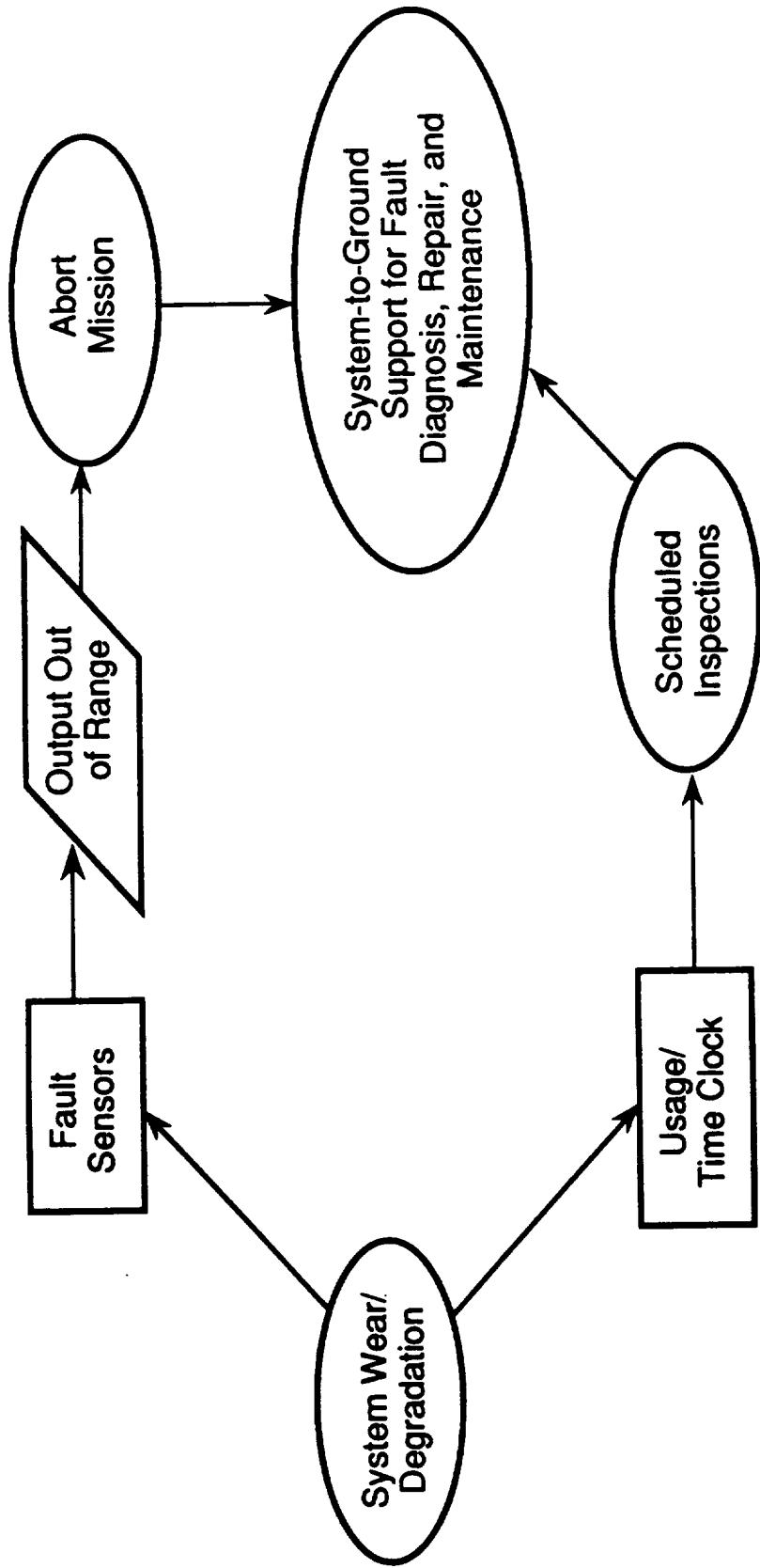
Honeywell Perspective— A Systems View



- A health management system—
- Monitors, evaluates and diagnoses system health; it integrates the following elements:
 - Nominal system status/configuration/nominal operation/checkout data
 - On-line condition and safety monitoring
 - Predictive and preventive diagnosis
 - Fault detection, isolation, recovery (including BIT)
 - Explanation and recommendation facility
 - Integrated maintenance database
 - Is part of an integrated launch system controls architecture that provides life-extending control to maintain assets and reduce replacement costs, as required

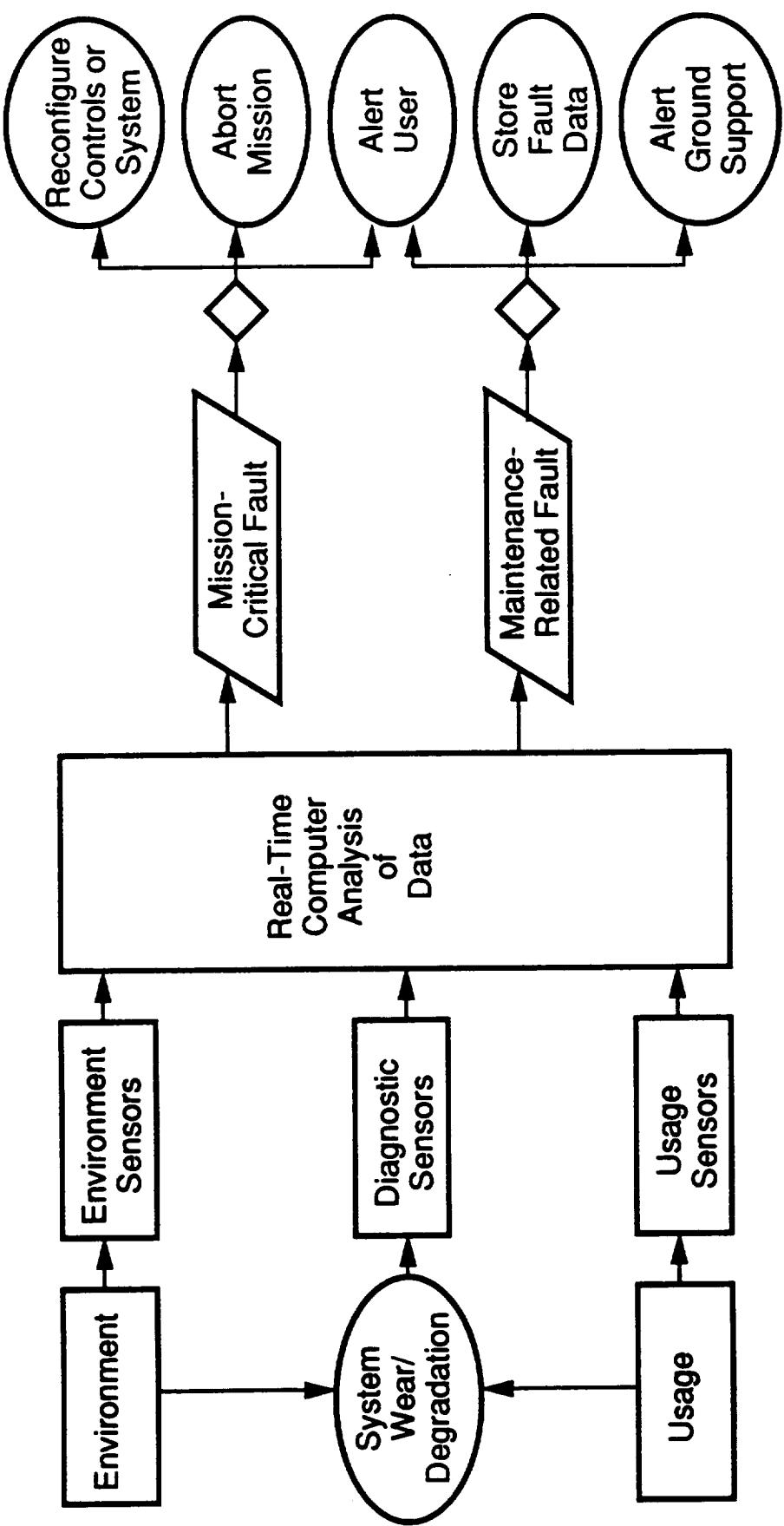
Health-Monitoring Systems

The Present Situation

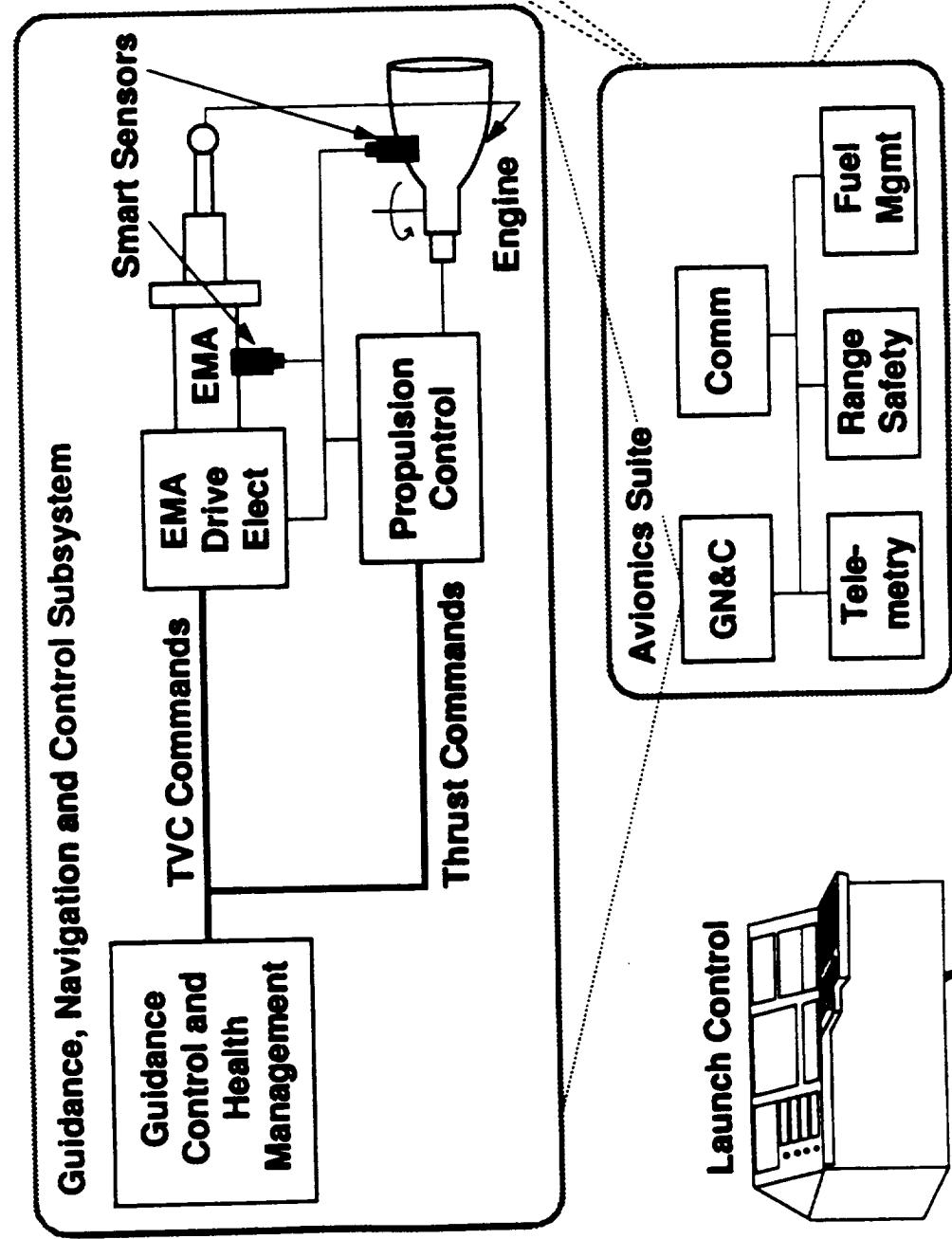


Health-Monitoring Systems

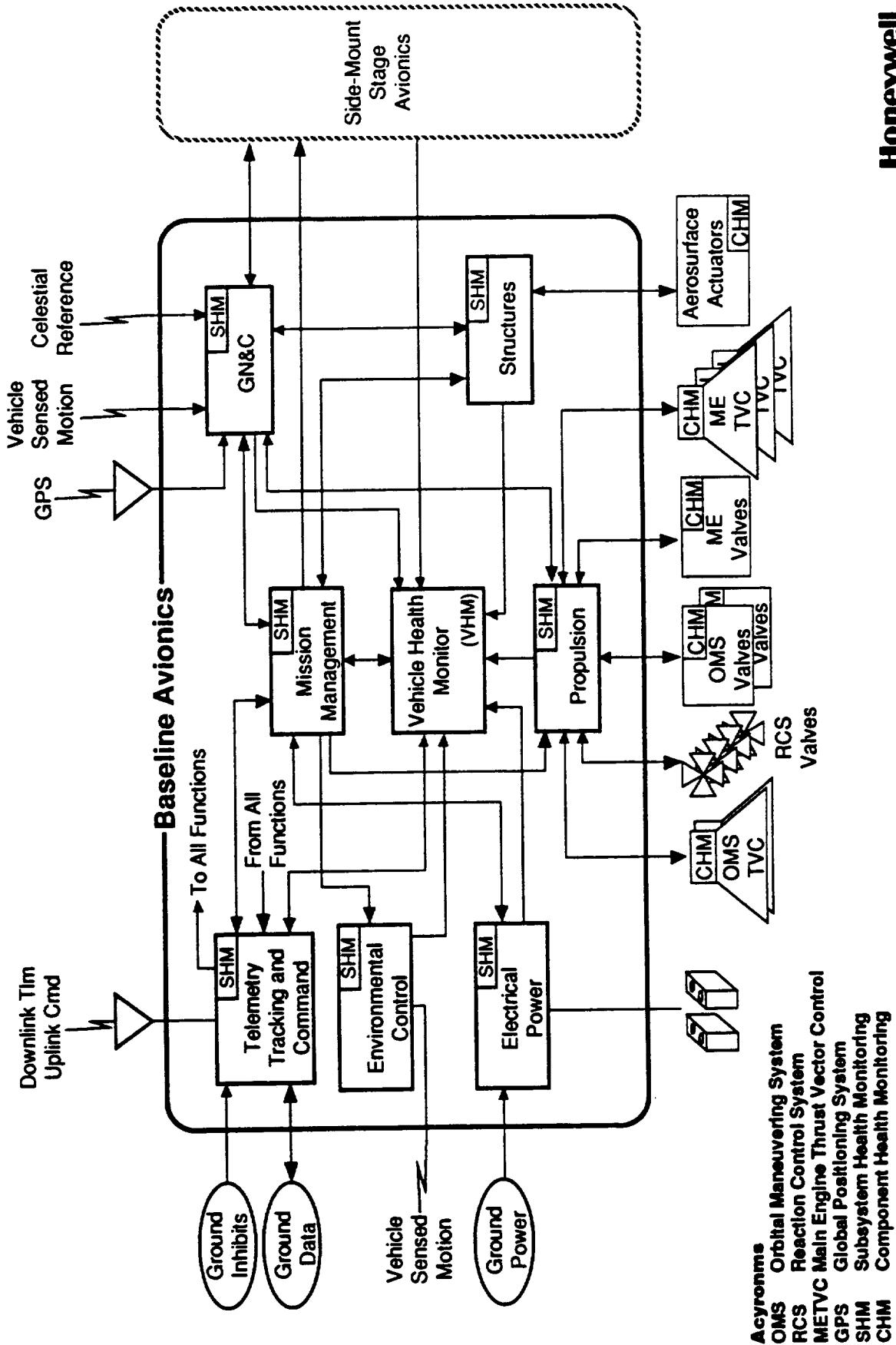
The Future



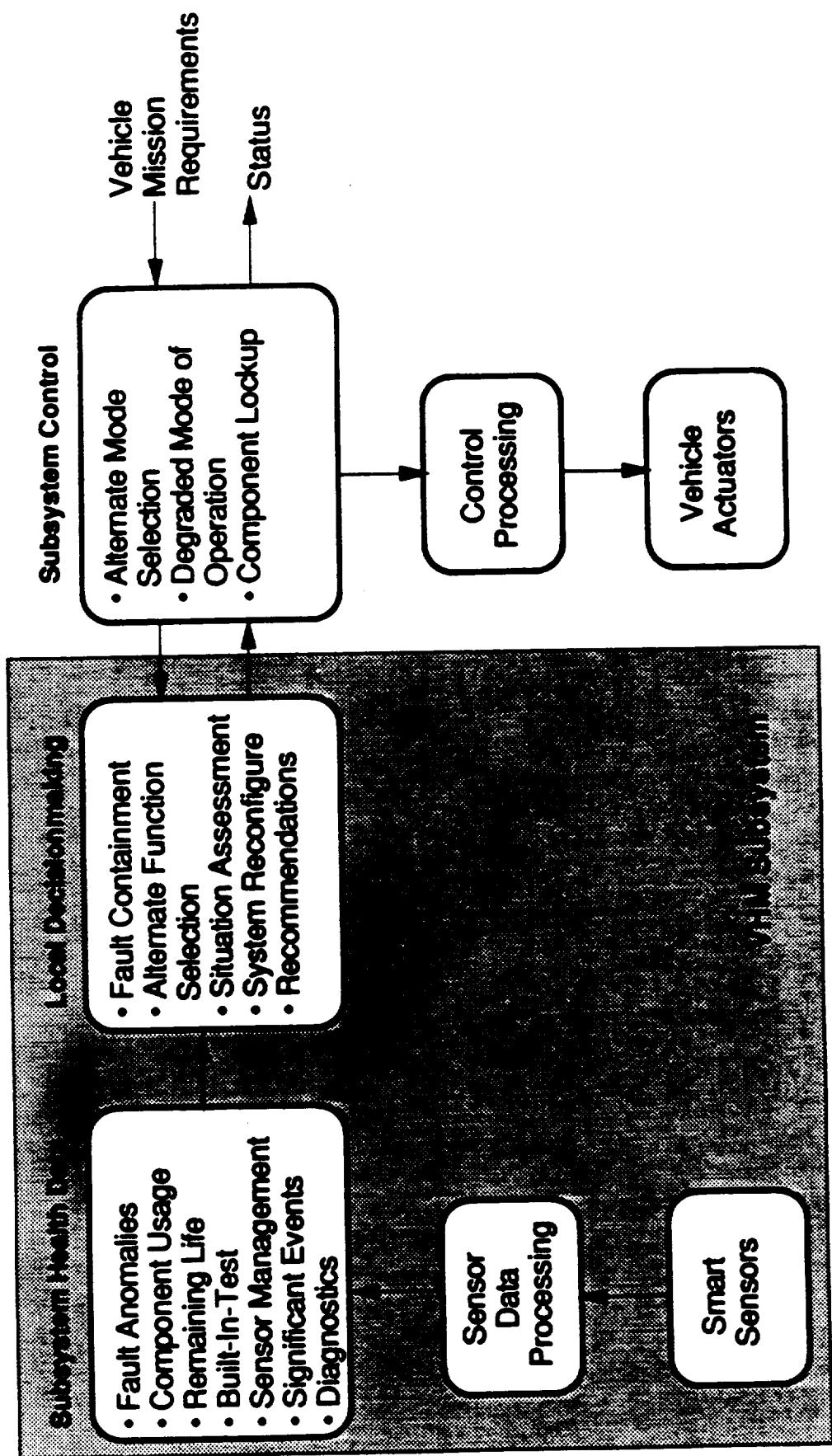
Advanced Launch System Health Management Approach



HLV Baseline Avionics Configuration



VHM Integration Logic Flow



Smart Structures Functionality Definition

Vehicle Goals

- Fault avoidance
- Reduced maintenance on schedule/demand
- Remaining life

System Goals

- Automated checkout
- Real-time monitoring
- Integrated Maintenance
- Fault prognosis/diagnosis
- Information management and control

Subsystem Goals

- Resource allocation
- Fault prediction, detection, isolation
- Redundancy management
- Local data management and control
- Significant event detection

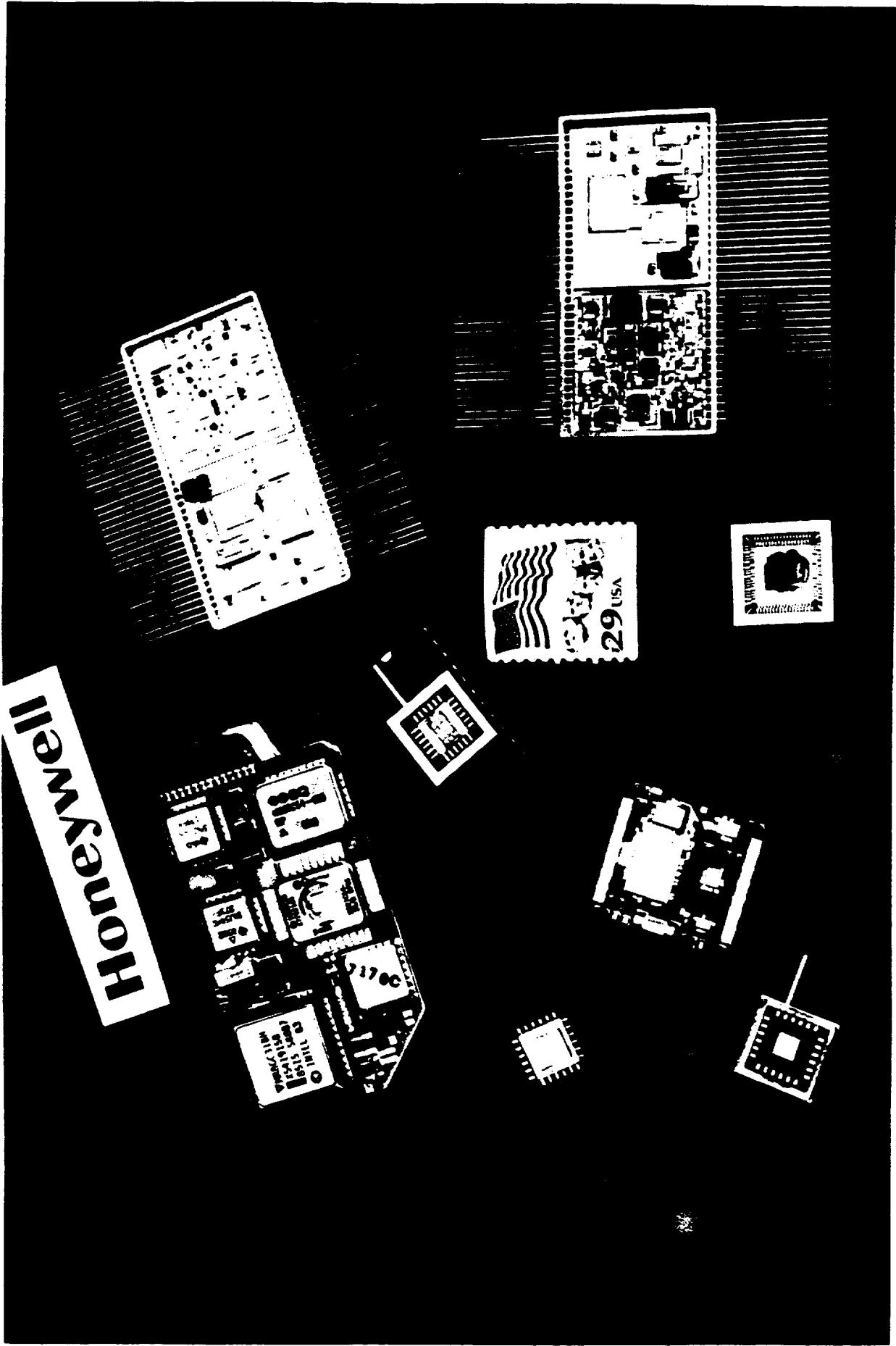
Smart Sensor

- Fault detection and isolation
- Self-test
- Local data qualification
- Time-stamping of data
- Data reasonability tests

Honeywell

ME2004-08

Smart Sensor Microsystems

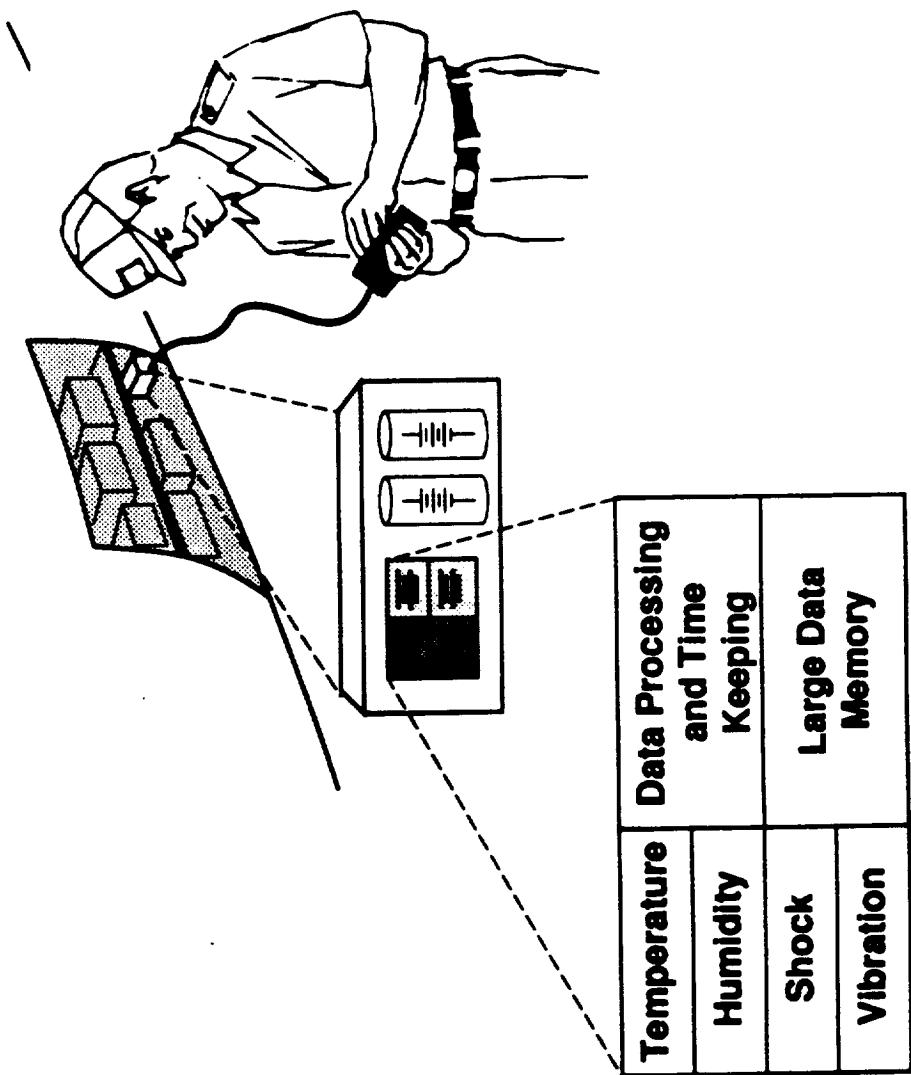


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Systems and Research Center

Honeywell

Time and Stress Measurement Device



Time and Stress Measurement Device (TSMD)

A TSMD is a miniature electronic device or component which senses environmental stress parameters that can cause failures in electronic systems. These parameters are

- Vibration
- Shock
- Temperature
- DC voltage
- Voltage transients

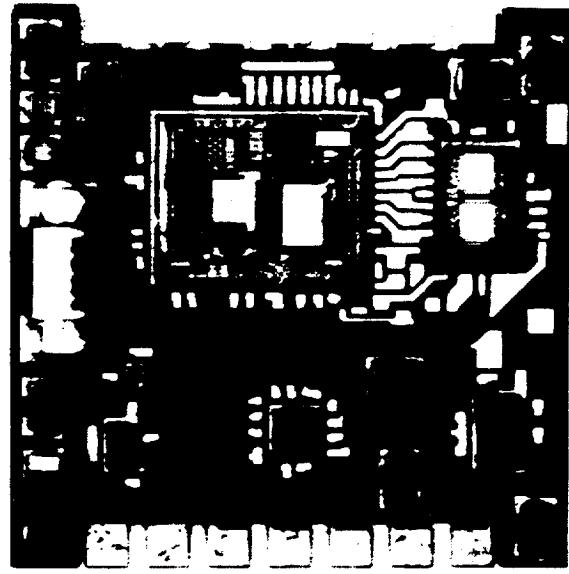
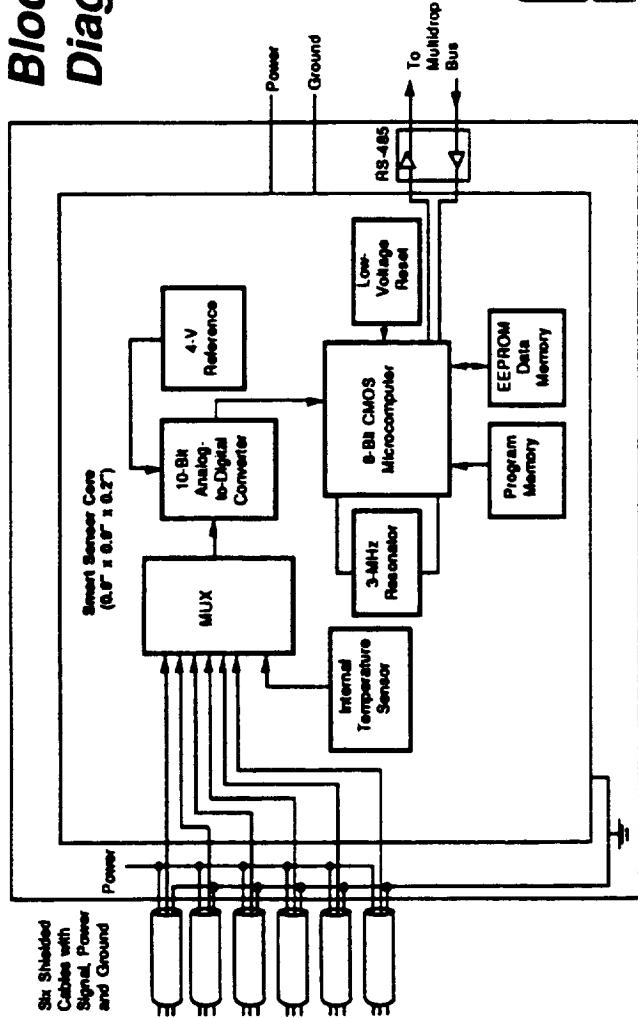
TSMD processes the stress data and stores it in nonvolatile memory

The TSMD is designed to accumulate stress data for months or years of use

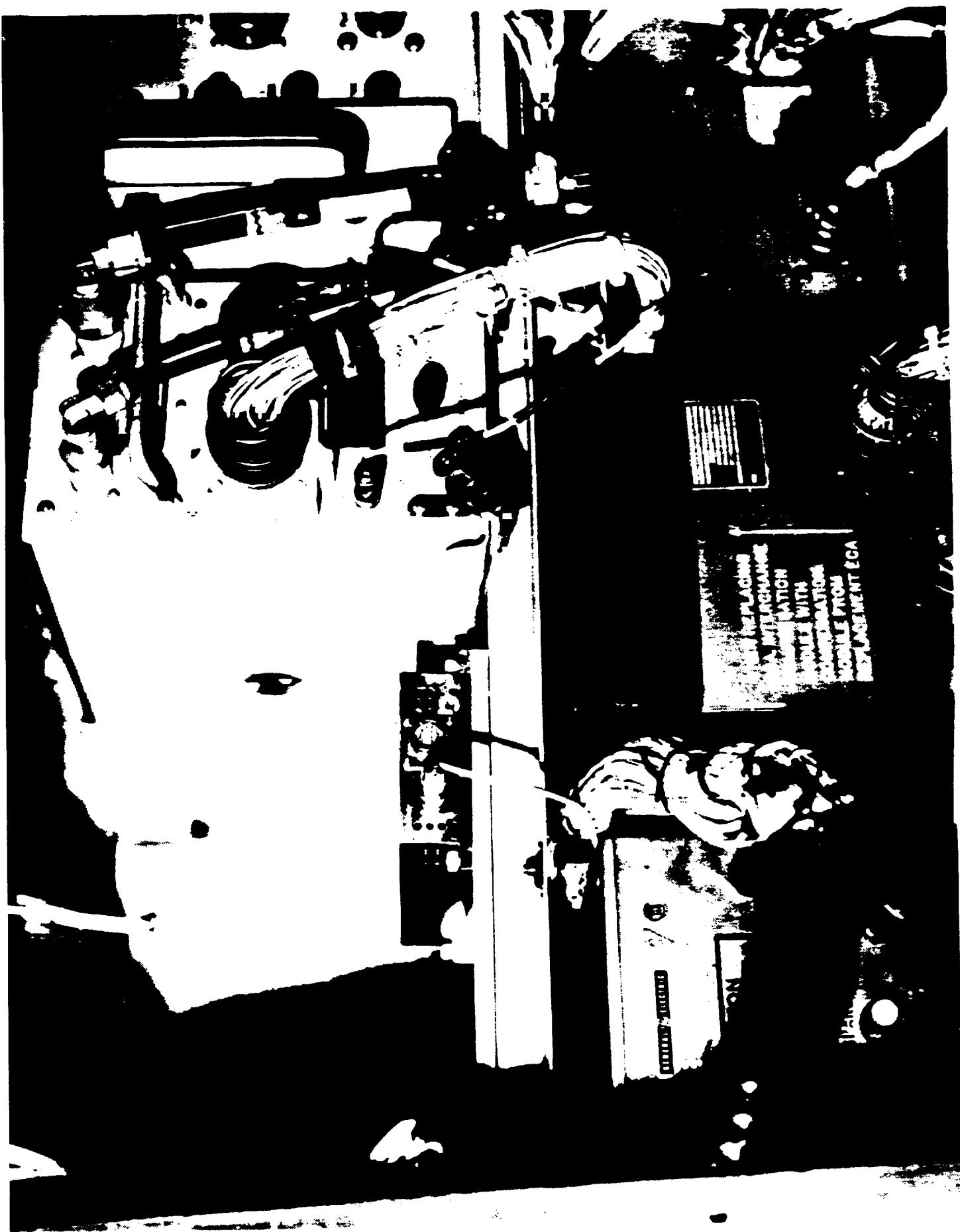
A real-time reference maintained by the TSMD can show the date and time of particular stress events

Smart Sensor Electronics Core

**Block
Diagram**

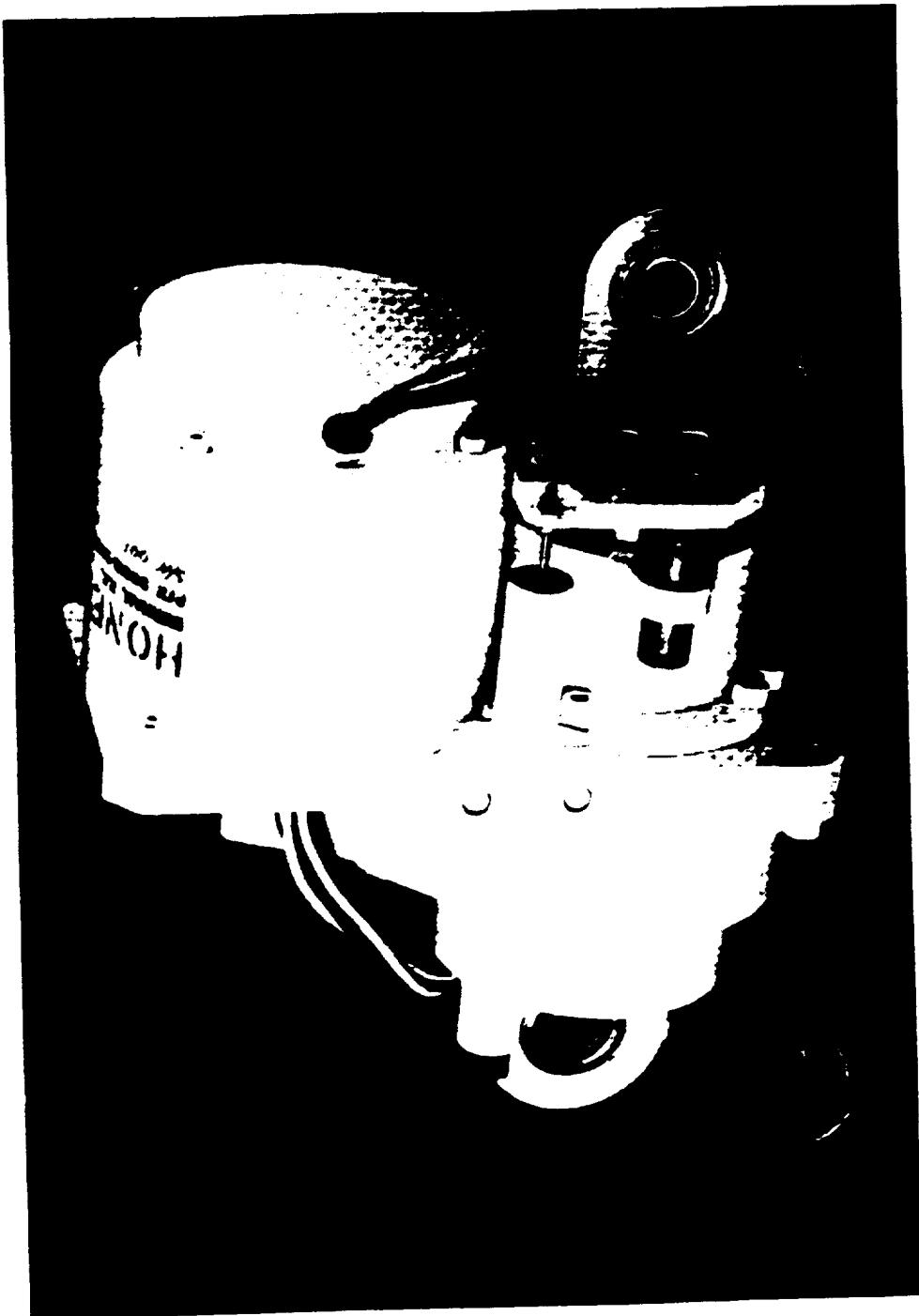


**Photo of
Smart Sensor
Electronics Core**



TSMD Module Mounted in A-10 Aircraft

Two-Horsepower Electromechanical Actuator



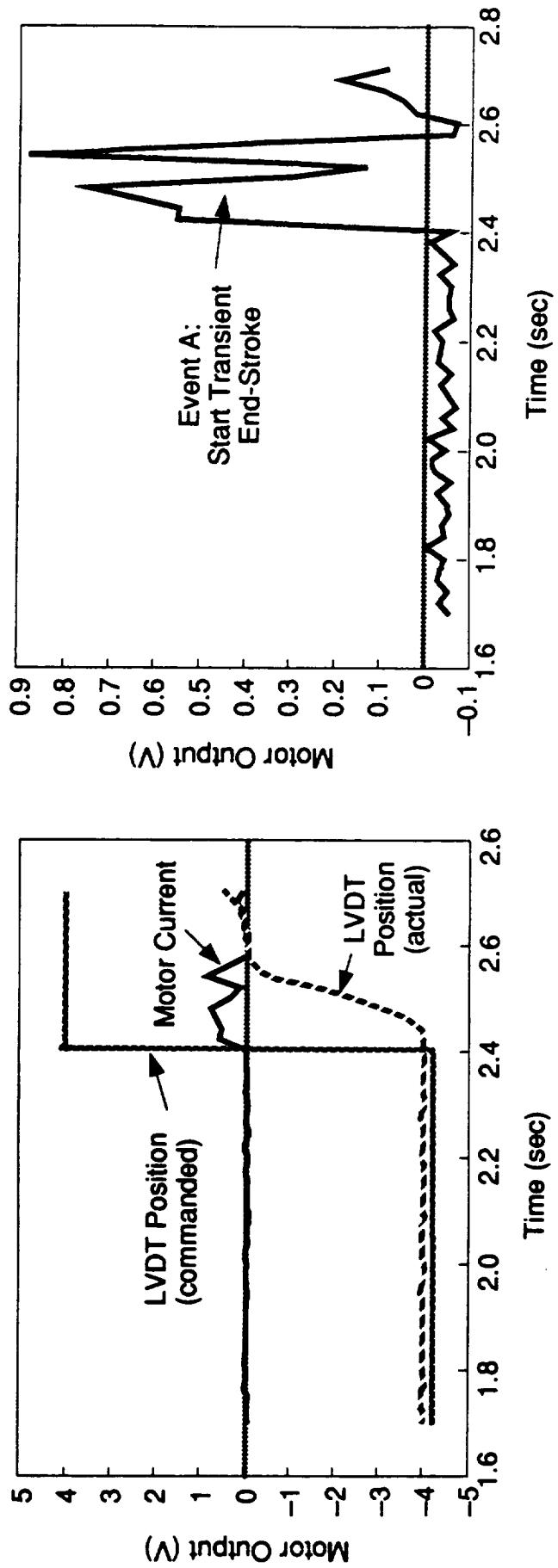
Honeywell

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Motor Current Assessment Matrix

Signature Analysis Motor Failure Modes	Failure Mode Effects	Motor Current Signature			Type of Failure
		Time Domain	Frequency Domain	-	
1 Loose/Corroded Electrical Connector	Loss of power due to open/short circuit	Random transients	Frequency shift	-	Degraded
2 Motor Winding Failure	Torque loss, power supply transient	Decreasing trend	Amplitude increase/decrease	Catastrophic	Catastrophic
3 Motor Gear Disengagement	Loss of motor actuation	Decreasing trend	Amplitude frequency shift	Degraded	Degraded
4 Motor Gear Tooth Breakage	Gear wear	Random transients	-	Catastrophic	Catastrophic
5 Lubrication Failure	Motor gear lockup	Start transient	-	-	Degraded
6 Gear Shaft Stiffness	Shaft wear	Start transient	-	-	Degraded
7 Motor Bearing Failure	Bearing race wear, ball bearing wear	-	Amplitude increase/decrease	Catastrophic	Catastrophic
8 Gear Interface Stop	Gear wear	Start/stop transients	Frequency shift	Degraded	Degraded
9 Motor Speed Slip	Intermittent operation	-	Frequency shift	Degraded	Degraded
10 Linear Actuator Stiction	Actuator wear	Start/stop transients	-	-	Degraded
11 Actuator Obstructions	Burn-out motor mechanisms	Increasing trend	Frequency shift	-	Catastrophic

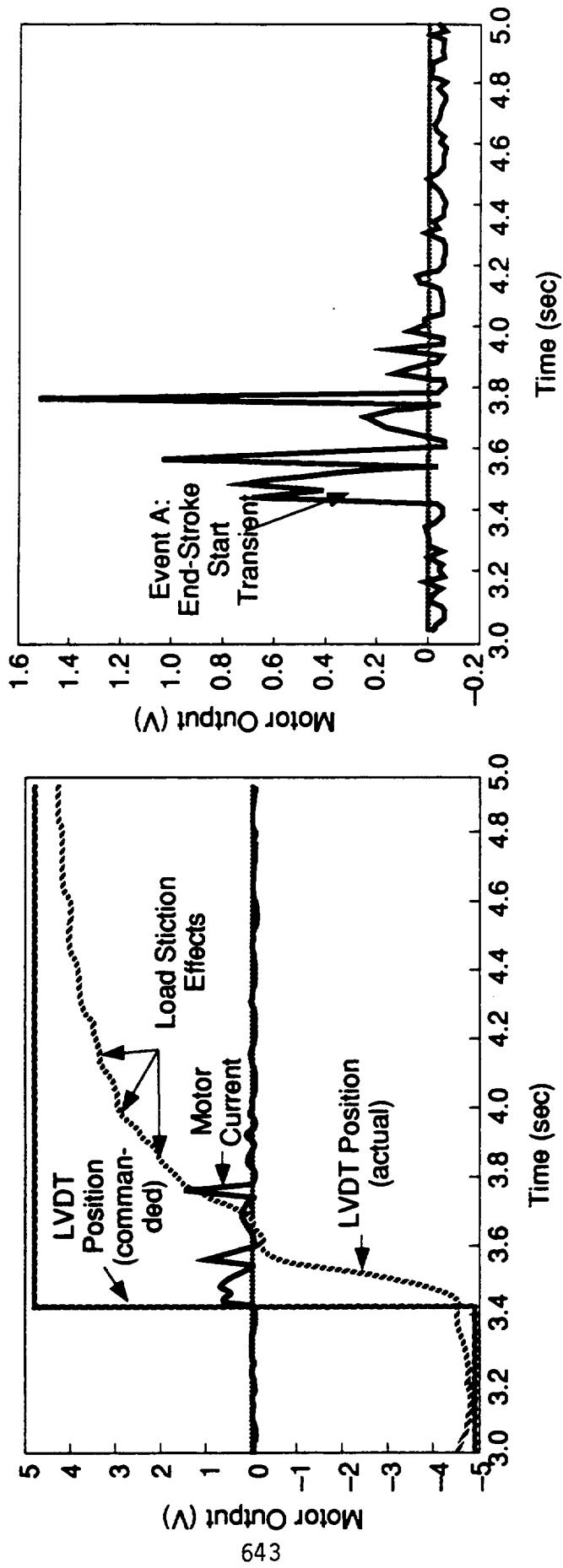
EMA Test 1: Loose Actuator Bearing Anomaly



Honeywell

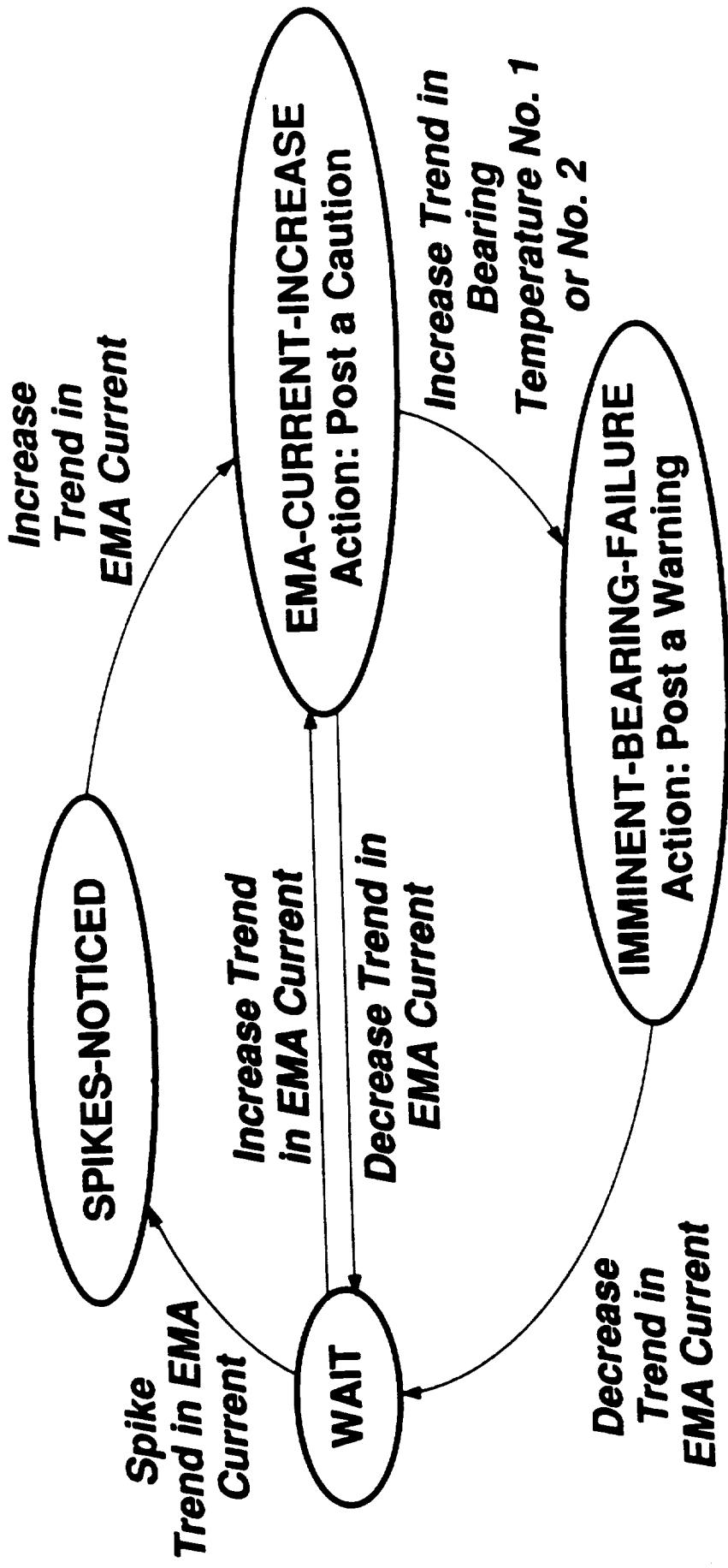
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EMA Test 2: Tightened Actuator Bearing Characteristics



643

EMA Bearing Wear Failure Prediction Example



Honeywell

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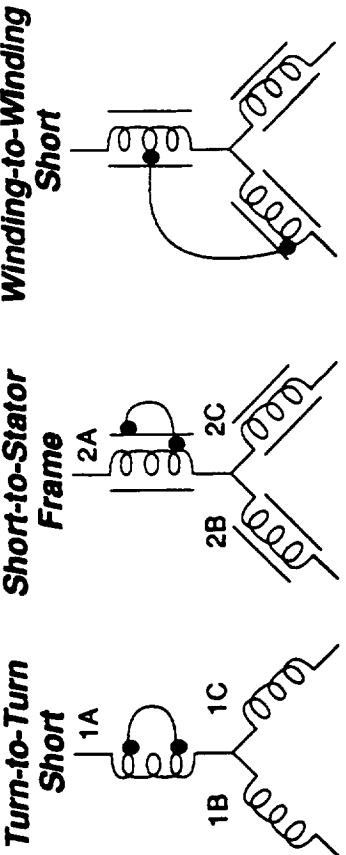
EMA Motor

Winding Failure Priority 2

Test Objective—to detect a motor winding failure due to emulsated failure of winding conductor or motor slot insulation

EMA Failure Mode—a failure of the EMA motor winding assembly; three possible failure scenarios:

- Normal to open circuit due to winding conductor failure (vibration, fatigue) or mechanical disconnect
 - Normal to short circuit due to insulation breakdown, wear
- Three types of shorts
1. Turn-to-turn short
 2. Short-to-stator frame
 3. Winding-to-winding short
- Short to open circuit due to excessive conductor heating

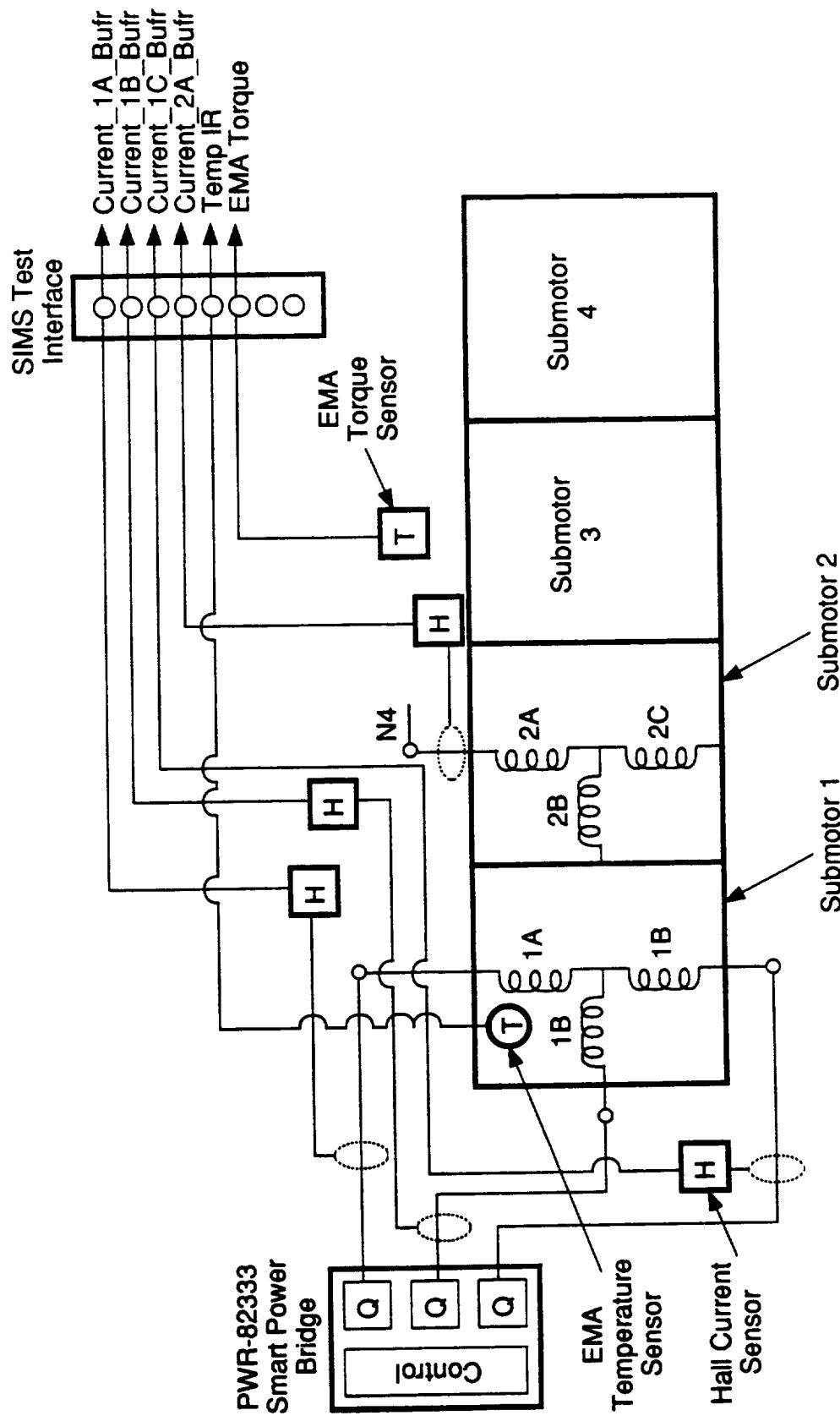


Type of Failure Mode	Characterization	Circuit Designation	Measured Parameters	Expected Results
Short Circuit	Short-to-station (local test)	1A to ground	• Current_1A • Torque • Temp_IR	• Significant torque loss (1/2 of submotor)
	Winding-to-winding (local test)	1A to 1B	• Current_1A, 1B • Torque • Temp_IR	• Torque loss (2/3 of submotor) • Torque drag effect
Submotor-to-submotor (global test)	1A to 2A	• Current_1A, 2A • Torque • Temp_IR		• Increased equivalent inductive load • Torque ripple effect • Ground current fault
Open Circuit	Winding node 1A	—	• Current_1A • Torque	• Torque loss (torque ripple effect)

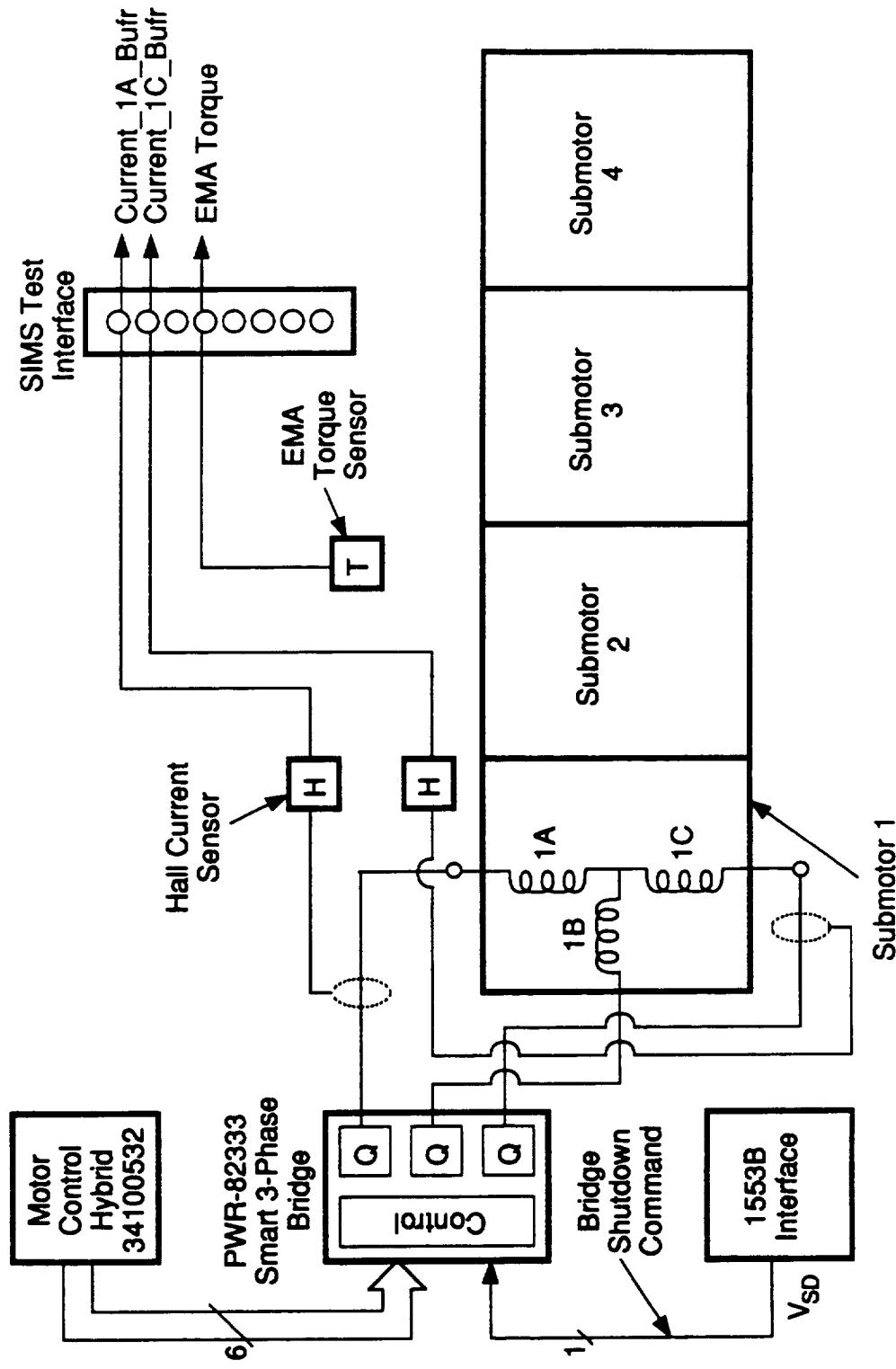
FMEA Characterization Procedure

1. Attach load to EMA actuator and command to move attached load at frequency of 0.5 Hz
2. Perform test sequence in table and record results

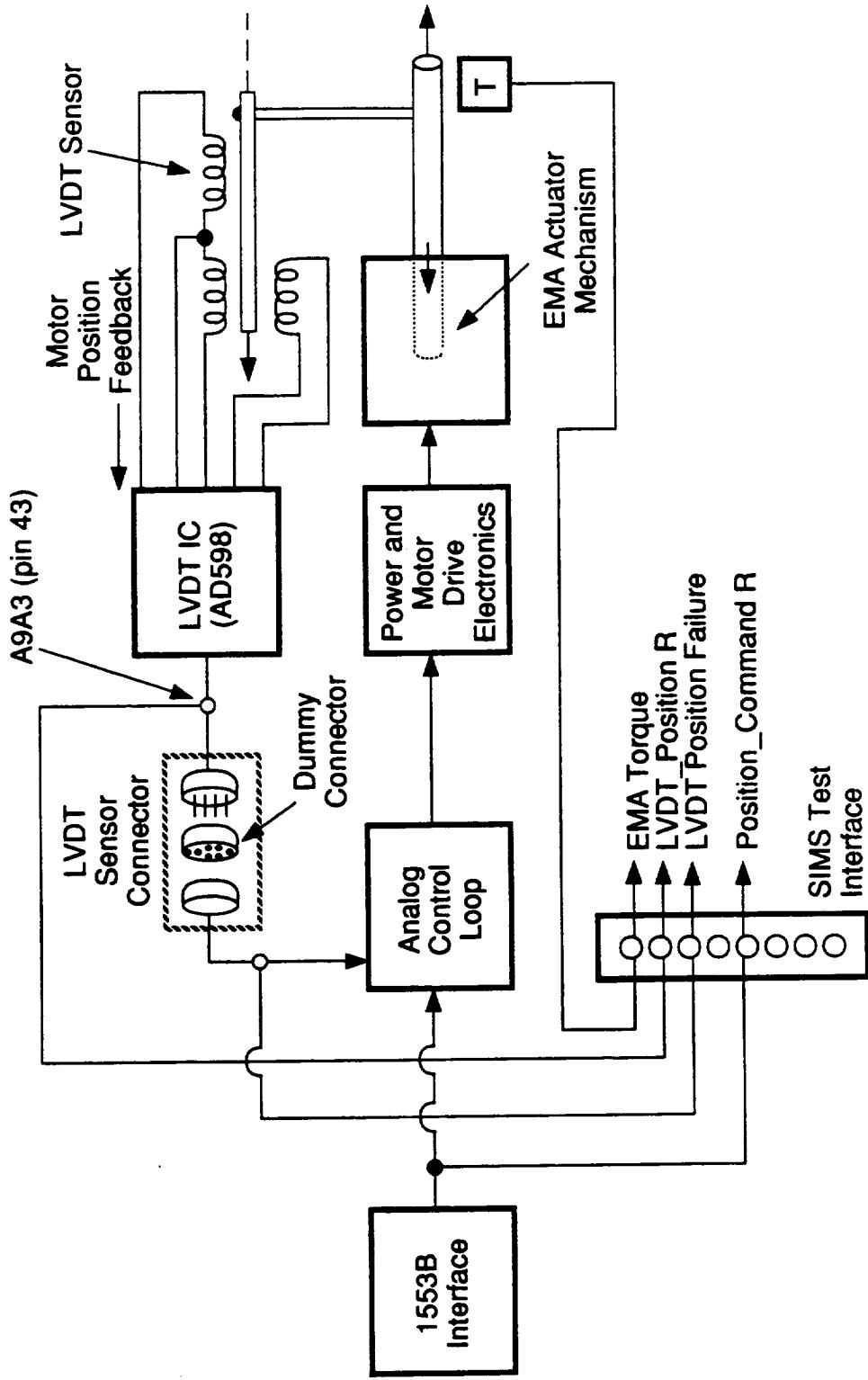
Motor Winding Failure Schematic



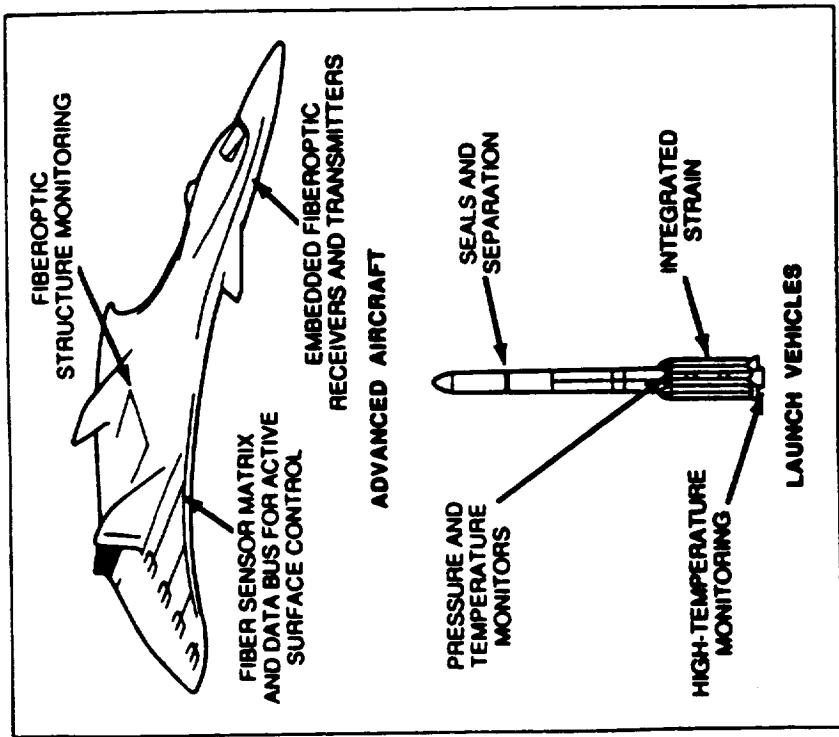
Power Transistor Failure Schematic



Loose Connector Failure Schematic



Signal and Data Acquisition Systems



Objective:

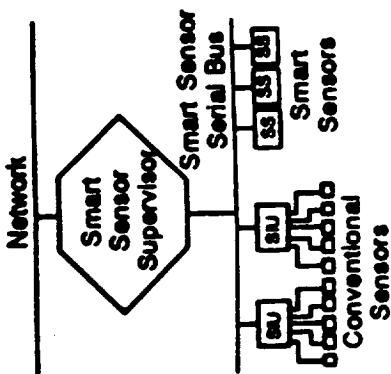
Smart Sensor Networks for Vehicle Health Monitoring

Features:

Detect and Isolate Potential Fault Anomalies via Built In Test (BIT)
Evaluate Subsystem Health Status/
Recommend Corrective Action

Applications

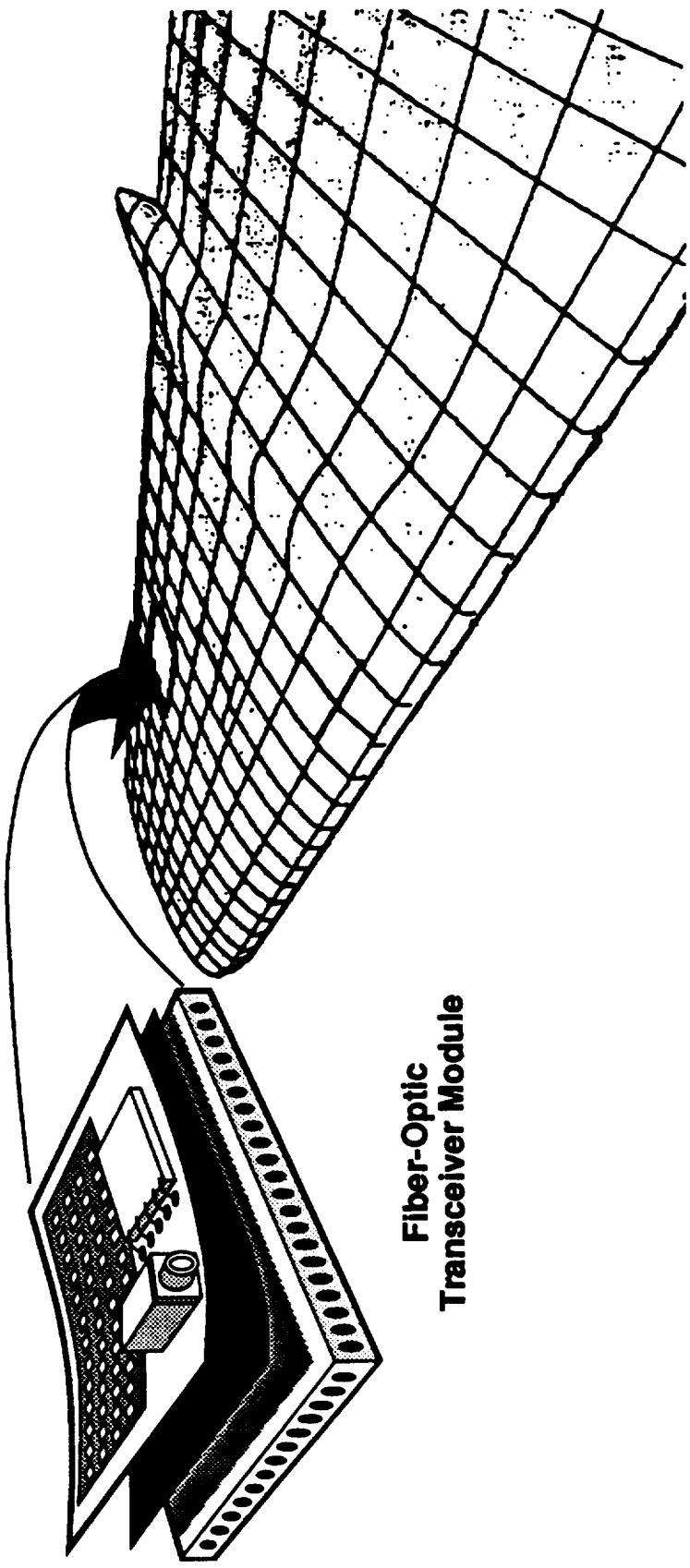
Structural Monitoring of Aging Aircraft
Launch Vehicle Integrity Assessment
Helicopter Mechanical System Monitoring
Space Platform Damping and Pointing
Nuclear Reactor Monitoring



Smart Structure Concept

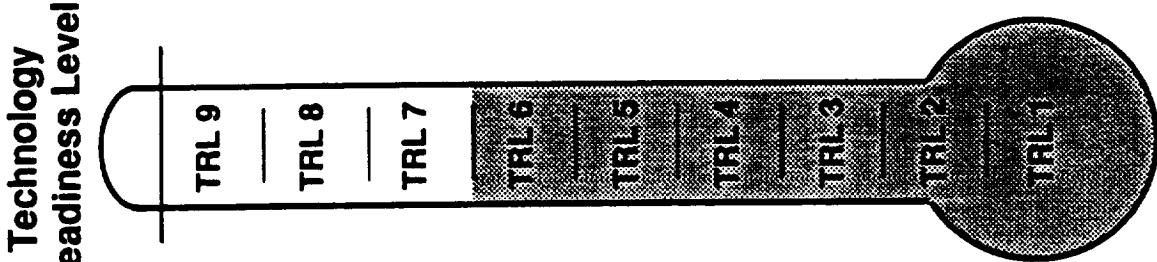
*Skin-Deep, Smart Sensors May Blanket
Future Aircraft to Detect and Isolate Internal
Structural Damage Characteristics*

Piezo AE Sensing
Array Elements



Smart Sensors

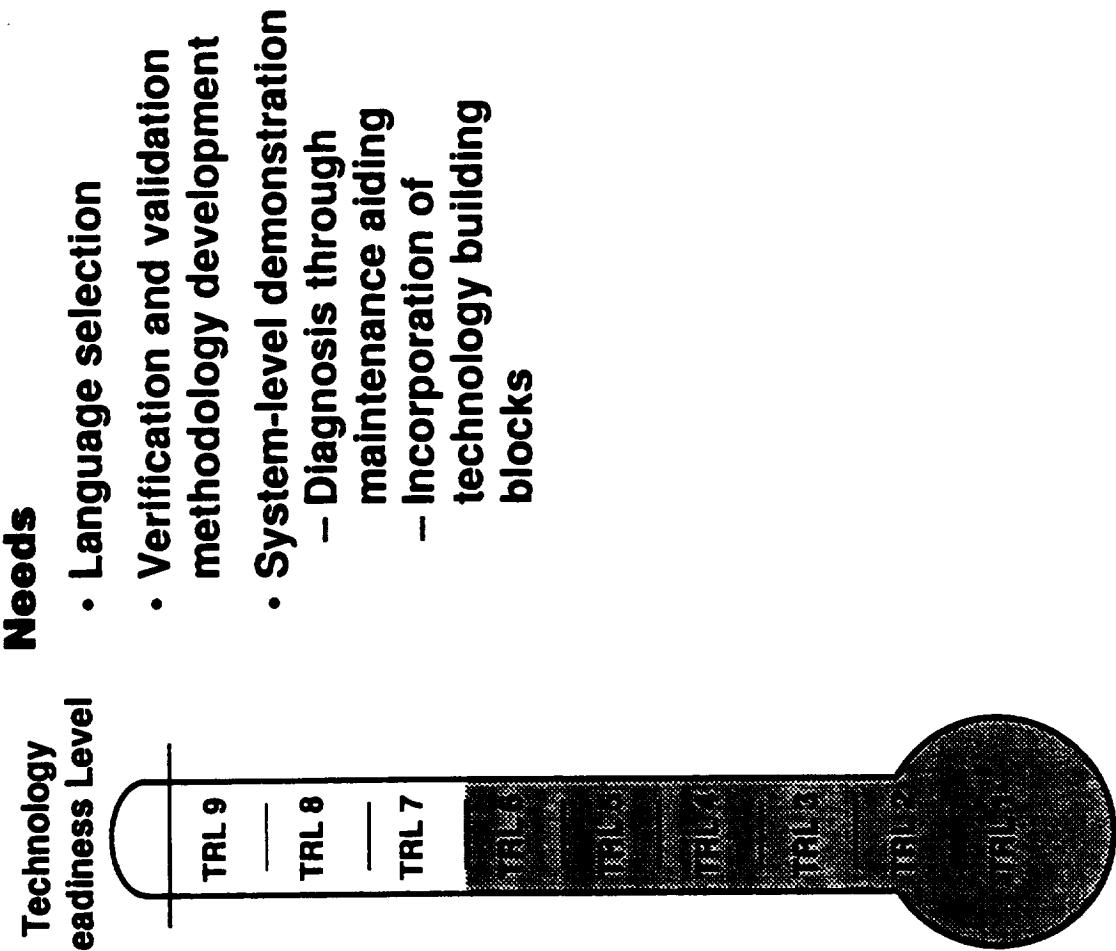
- | Lessons Learned | Technology Readiness Level | Needs |
|---|----------------------------|--|
| • Reduces wire weight significantly | TRL 9 | • Selection of applications |
| • Supports multisensor commonality and modularity | TRL 8 | • Selection of packaging approach |
| • Supports significant local information processing, communication, and integration | TRL 7 | • Development of high-temperature components |
| • Permits low-power implementations | TRL 6 | • Selection of standards |
| • Permits BIT at low system levels | TRL 5 | |
| • Allows I/O interface standardization | TRL 4 | |
| • Permits multiple applications to be met by one package (e.g., through reranging) | TRL 3 | |
| • Supports fault tolerance through redundant transducer packaging | TRL 2 | |
| | TRL 1 | |



Maintenance Diagnostics and Intelligent Algorithms

Lessons Learned

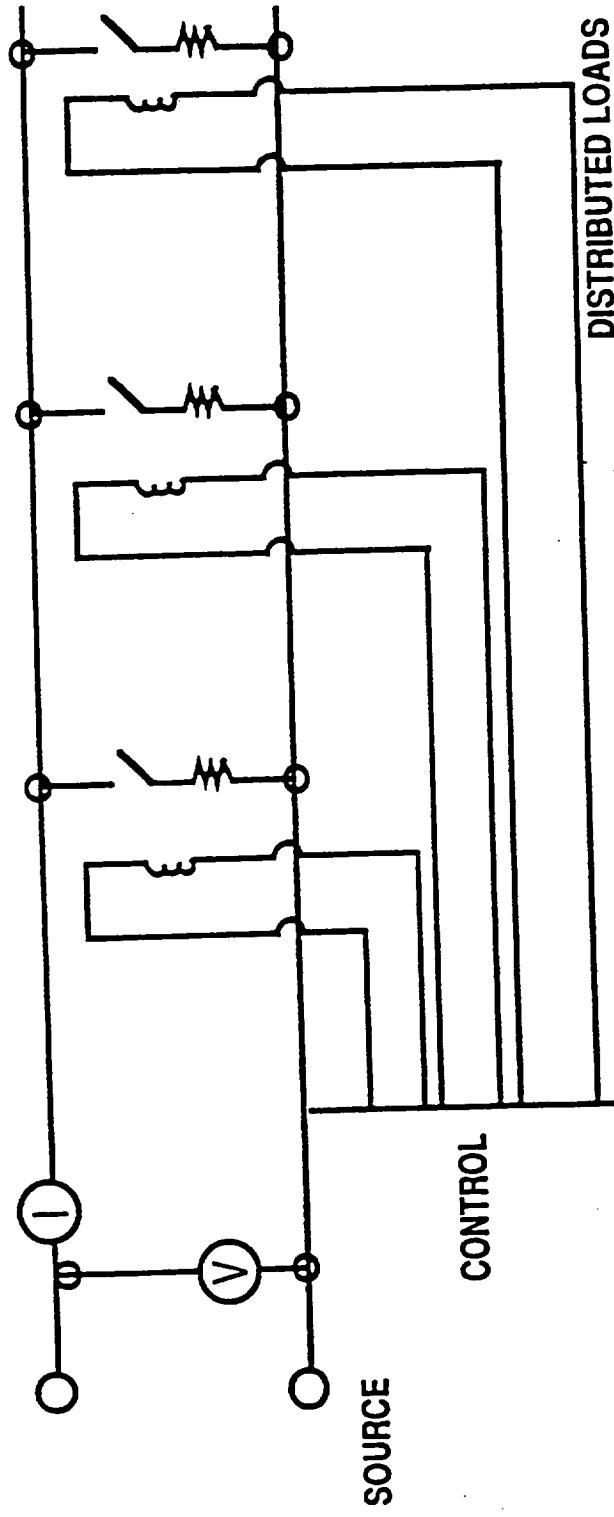
- Health monitoring algorithms do not require dedicated health monitoring sensors
- Predictive diagnostic algorithms can be developed for specific cases for systems that have a design heritage
- Maintenance systems pay for themselves through productivity improvements
- Data filter state monitoring and trend monitoring algorithms are computationally efficient
- Development requires close cooperation among domain experts, users, and maintenance system designers



**Intelligent Built-In Test
for
Electric Actuators**

Irving Hansen
NASA Lewis Research Center
Cleveland, Ohio

DISTRIBUTED POWER/CENTRALIZED CONTROL



TRADE - CONTROL WIRE FOR POWER WIRE
ATTEMPT TO MONITOR FROM CENTRAL MEASUREMENTS
UTILITY - STATE ESTIMATION ROUTINES

LESSON: SPACE STATION EXPERIENCE

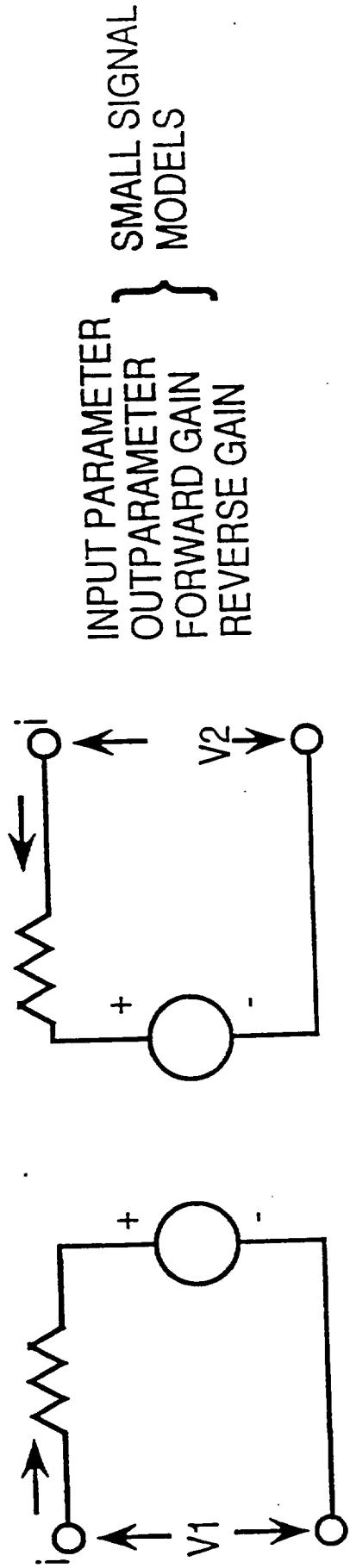
2 200 COMBINATIONS - 1.5 MILLION LINES OF CODE WHEN ABANDONED

LESSON: THREE MILE ISLAND - SENSED THAT COMMAND WAS SENT NOT THAT VALVE HAD MOVED
BROWNS FERRY - PUT POWER WIRE AND CONTROL WIRE IN SAME CONDUIT

LESSON: "DON'T LET SOFTWARE PEOPLE DESIGN YOUR POWER SYSTEM"

BUILT IN TEST

NON INTRUSIVE - ("FIRST DO NO HARM")
SYSTEM STATUS, REDUNDANCY STATUS, PROBABLE HEALTH
CALIBRATION AND VERIFICATION OF BIT AT EVERY CHECKOUT CONTINUOUSLY
FROM DESIGN TO DEPLOYMENT
(e.g. TESTBED, ACCEPTANCE, QUALITY TEST, PREFLIGHT)
RAPID RESPONSE, HIGH PROBABILITY OF CORRECT DECISION
SYSTEM ELEMENTS MODELED AS TWO PORT, FOUR TERMINAL NETWORKS



(TOP DOWN) - SYSTEM REQUIREMENTS



VEHICLE HEALTH MANAGEMENT

GENERAL:

- FAILURE TOLERANCE (ROBUSTNESS e.g., FAIL OP, FAIL OP, FAIL SAFE)
(QUAD REDUNDANCY A SOLUTION NOT A REQUIREMENT)

- DETECTION - BUILT IN TEST
- CONTAINMENT - DESIGN AND PROTECTION

- ACCOMMODATION - REDUNDANCY MANAGEMENT

FUZZY LOGIC

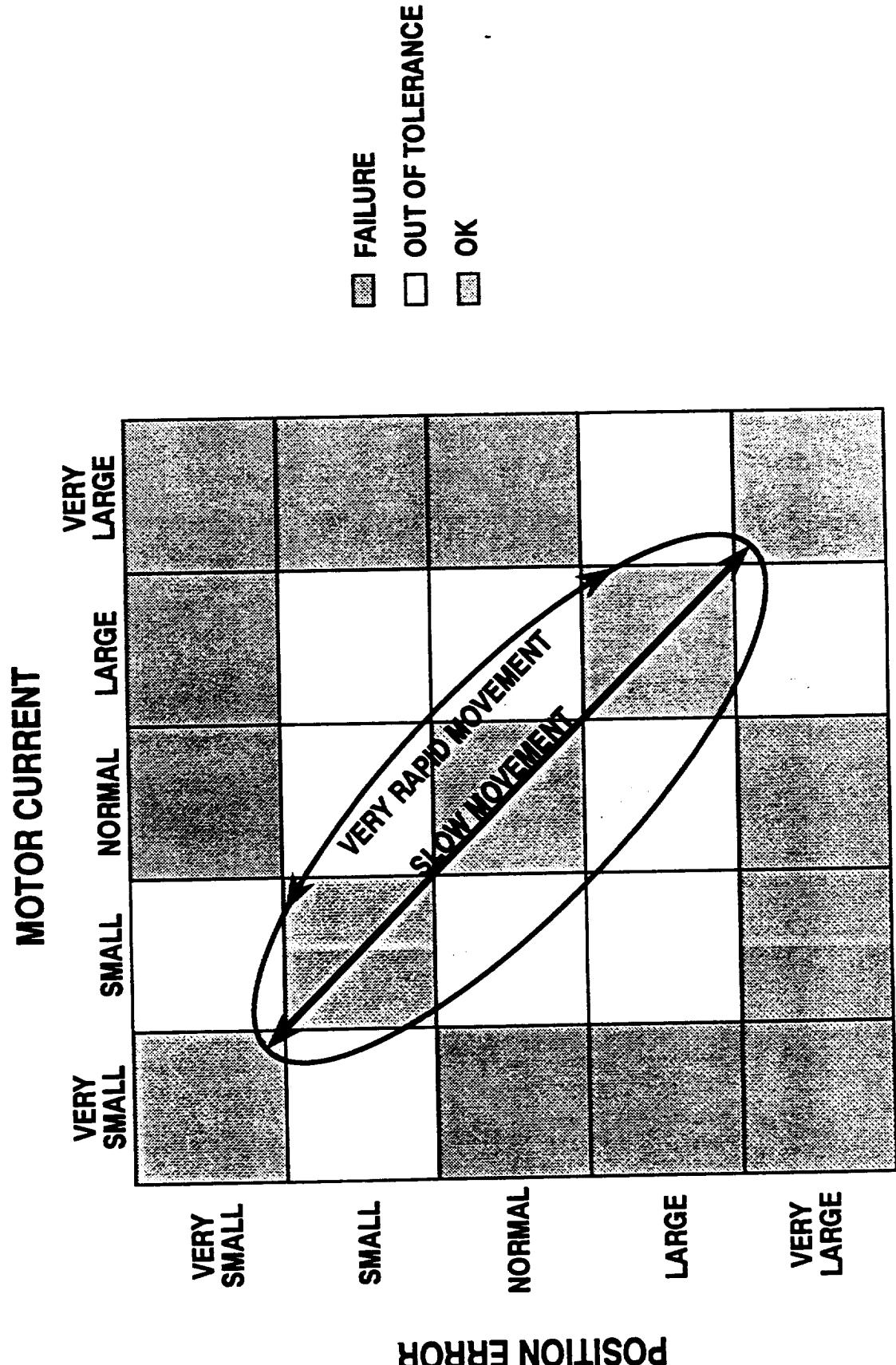
THE LOGIC OF HANDLING FUZZY INFORMATION
ADJECTIVES - MORE, LESS, FASTER, SLOWER (FUZZY QUANTIZATION)
CRISP SETS - 0,1 PRECISE QUANTIZATION
APPLICATION TO BUILT IN TEST OF TWO PORT NETWORKS
INPUT - ERROR SIGNAL (OR COMMAND)
OUTPUT - CURRENT OR VOLTAGE } CRISP DATA
FORWARD GAIN - RATIO OF OUTPUT TO INPUT }

e.g. FUZZY LOGIC AND EXPERT SYSTEM APPLICATIONS - B. K. BOSE, UNIVERSITY OF TENNESSEE, KNOXVILLE

"IF SPEED LOOP IS NEAR ZERO, AND ERROR RATE OF CHANGE IS SLIGHTLY POSITIVE, THEN CONTROL SHOULD BE A SMALL NEGATIVE"

RESULT - CONTINUOUS NON INTRUSIVE MONITOR OF SERVO GAIN

FUZZY LOGIC RULE TABLE



EMA SPECIFIC REQUIREMENTS



(BOTTOM UP) - DESIGN ARCHITECTURE FOR:

**COMPONENT LEVEL - DIAGNOSTICS (NEURAL NETWORK, NOT IN REAL TIME)
(EVENTUAL INCIPIENT FAILURE DETECTION)**

**SUBSYSTEM LEVEL - RAPID DETECTION (NOT INTRUSIVE MEASUREMENT, WIDE
DYNAMIC RANGE, FOUR QUADRANT OPERATION)**

**APPROACH TAKEN - FUZZY LOGIC OBSERVED (CONTINUOUS MONITOR OF INPUT
(COMMAND) AND OUTPUT (CURRENTS & POSITION)**

**EVALUATION & CALIBRATION - HYBRID ANALOG COMPUTER AT PURDUE UNIVERSITY
(ALLOWS MAJOR FAULTS TO BE INTRODUCED WITHOUT
ENDANGERING PERSONNEL OR EQUIPMENT)**

Rapid, VHM System For Electrical Actuation/Power/Avionics

Task Objectives/Benefits	Demonstration/Bridging Approach																																				
<p>Objective(s): Develop and demonstrate automated, rapid self-check systems for advanced electrical actuators and effectors, power and avionic systems including more-electric ground support equipment (GSE)</p> <p>Applicable Vehicles: ELV, NLS, Upper Stages, STS Upgrades, AMLS, ACRV</p> <p>Benefits:</p> <ul style="list-style-type: none"> Transfer rapid prototyping steps to improve vehicle assembly, ground operations and launch sequencing Demonstrate "bottoms-up" HW/SW platform for interface to total IHM system Reduce launch system costs Improve launch system operability, reliability and safety 	<p>Task(s):</p> <ol style="list-style-type: none"> 1. Develop specific elements to existing (SBIR II) detailed models/ simulations of vehicle and GSE systems under normal and fault conditions <ol style="list-style-type: none"> a. Insert fault, document parameter variations b. Validate model predictions, characteristics on subsystem hardware 2. Integrate HW/SW for rapid BIT on existing DSPs to demonstrate health indicators on selected electrical equipment (EMAs and power system) 3. Test/demonstrate BIT under fault conditions and selected fault modes to validate technology/models 4. Develop interfaces to top level IHM system and automate responses to detected fault modes 5. Validation assessment of technology <p>Available Facilities: LeRC Technology Demonstration Facility, Autonomous Power System, EMA Laboratory, and University of Purdue Hybrid Computer Facility</p>																																				
Schedule/Cost																																					
	<table border="1" data-bbox="912 128 1516 1058"> <thead> <tr> <th data-bbox="912 128 994 846">TASK</th><th data-bbox="994 128 1075 846">FY 93</th><th data-bbox="1075 128 1156 846">FY 94</th><th data-bbox="1156 128 1238 846">FY 95</th></tr> </thead> <tbody> <tr> <td data-bbox="912 846 994 1058">1</td><td data-bbox="994 846 1075 1058"></td><td data-bbox="1075 846 1156 1058"></td><td data-bbox="1156 846 1238 1058"></td></tr> <tr> <td data-bbox="994 846 1075 1058">1a</td><td data-bbox="1075 846 1156 1058"></td><td data-bbox="1156 846 1238 1058"></td><td data-bbox="1238 846 1319 1058"></td></tr> <tr> <td data-bbox="1075 846 1156 1058">1b</td><td data-bbox="1156 846 1238 1058"></td><td data-bbox="1238 846 1319 1058"></td><td data-bbox="1319 846 1400 1058"></td></tr> <tr> <td data-bbox="1156 846 1238 1058">2</td><td data-bbox="1238 846 1319 1058"></td><td data-bbox="1319 846 1400 1058"></td><td data-bbox="1400 846 1482 1058"></td></tr> <tr> <td data-bbox="1238 846 1319 1058">3</td><td data-bbox="1319 846 1400 1058"></td><td data-bbox="1400 846 1482 1058"></td><td data-bbox="1482 846 1516 1058"></td></tr> <tr> <td data-bbox="1319 846 1400 1058">4</td><td data-bbox="1400 846 1482 1058"></td><td data-bbox="1482 846 1516 1058"></td><td data-bbox="1516 846 1516 1058"></td></tr> <tr> <td data-bbox="1400 846 1482 1058">5</td><td data-bbox="1482 846 1516 1058"></td><td data-bbox="1516 846 1516 1058"></td><td data-bbox="1516 846 1516 1058"></td></tr> <tr> <td data-bbox="1482 846 1516 1058">RESOURCES</td><td data-bbox="1482 846 1516 1058">0.15 M</td><td data-bbox="1482 846 1516 1058">0.3 M</td><td data-bbox="1482 846 1516 1058">0.3 M</td></tr> </tbody> </table>	TASK	FY 93	FY 94	FY 95	1				1a				1b				2				3				4				5				RESOURCES	0.15 M	0.3 M	0.3 M
TASK	FY 93	FY 94	FY 95																																		
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RESOURCES	0.15 M	0.3 M	0.3 M																																		

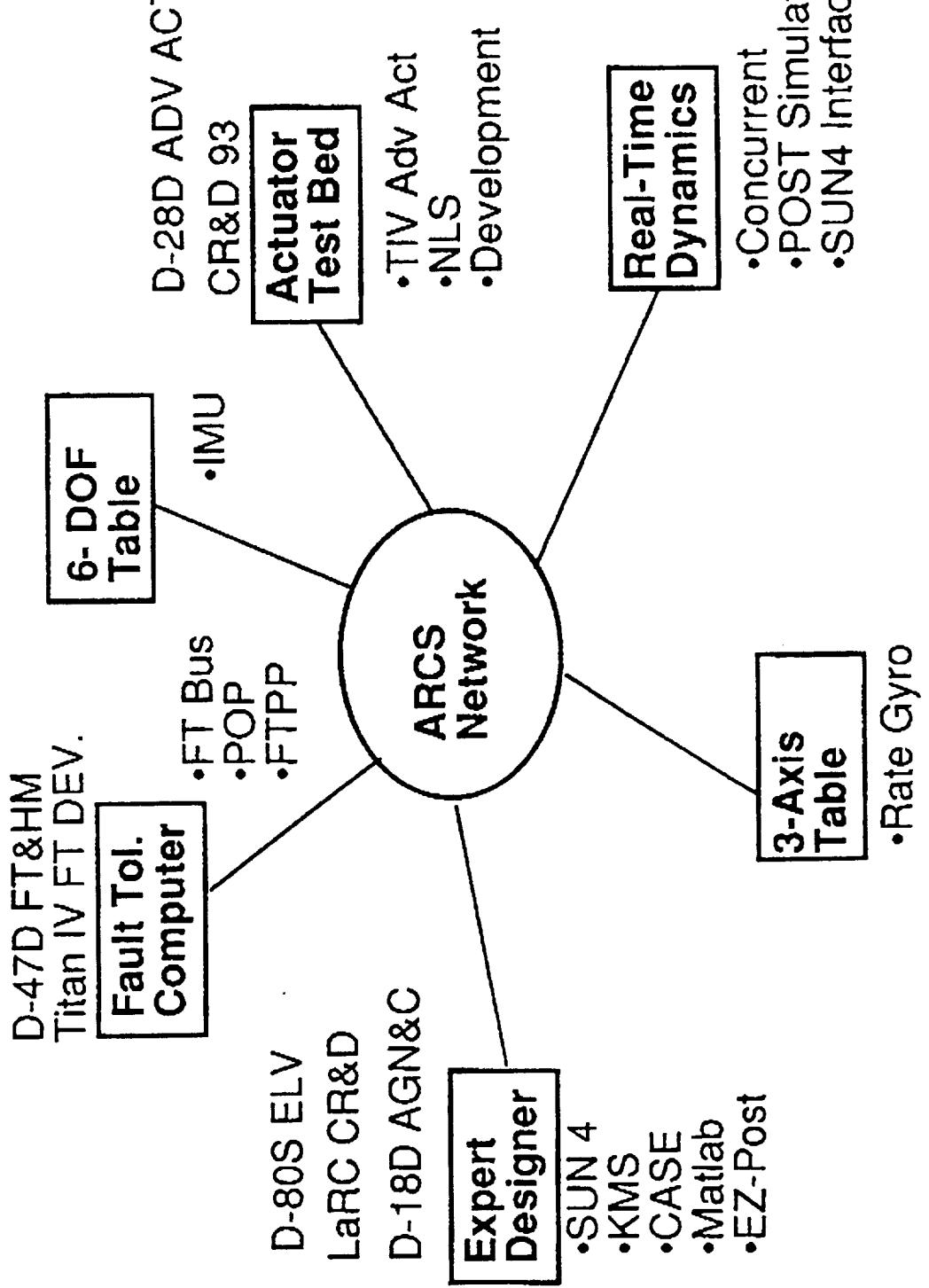
FAULT TOLERANT SYSTEM TESTING

**Norm Osborne
and
Dave Wilks**

Fault-Tolerant System Test Bed

- Objective of Test Bed
- Fault Detection Functional Tests
- Health Monitoring Function Tests
- System Performance Testing
- System Optimization Demonstration
- System Development
- Subsystem Development

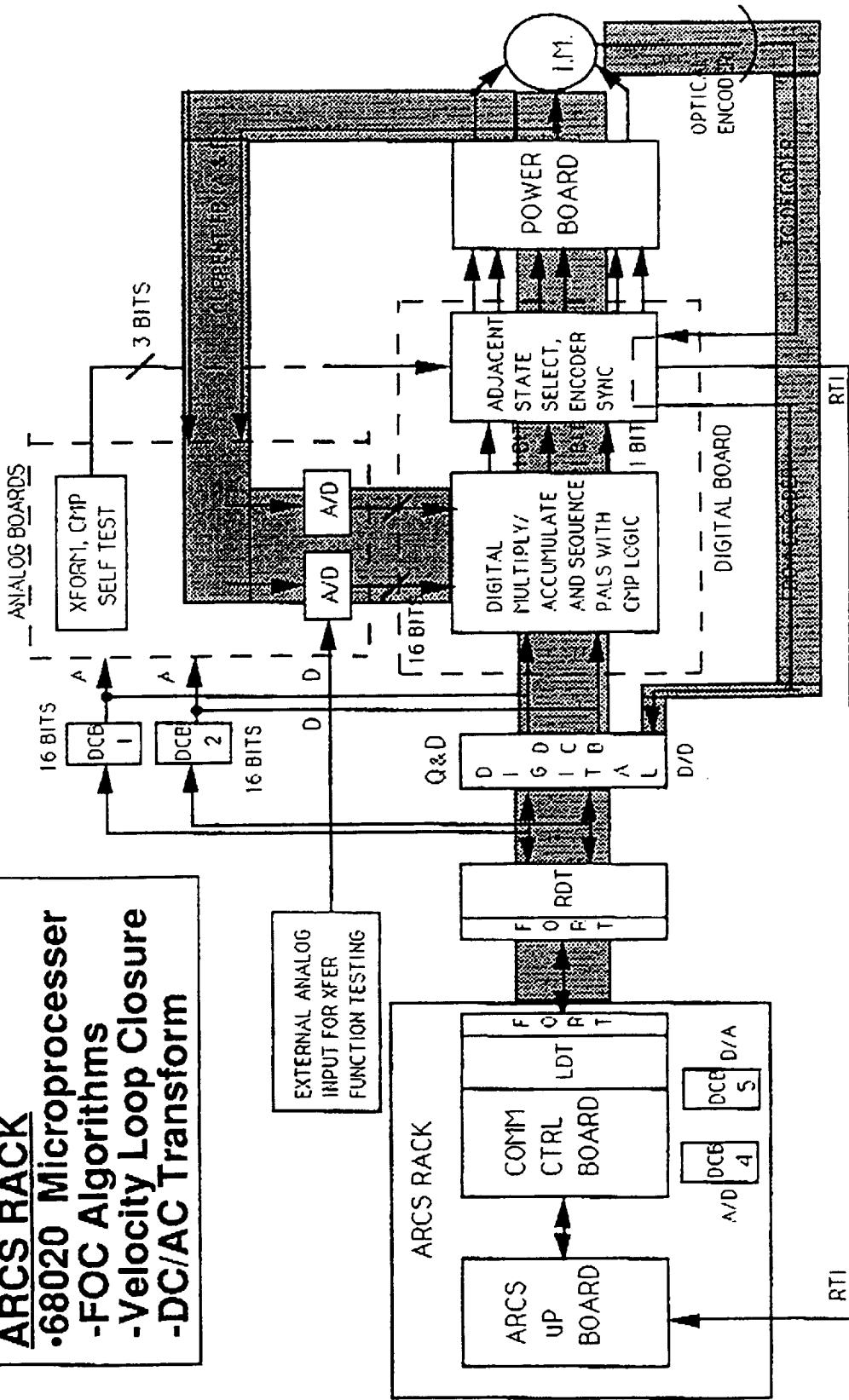
Fault-Tolerant System Test Bed Relationship with IR&D/ CR&D--Real-Time Lab



Fault-Tolerant System Test Bed EMA/ARCS TOPOLOGY

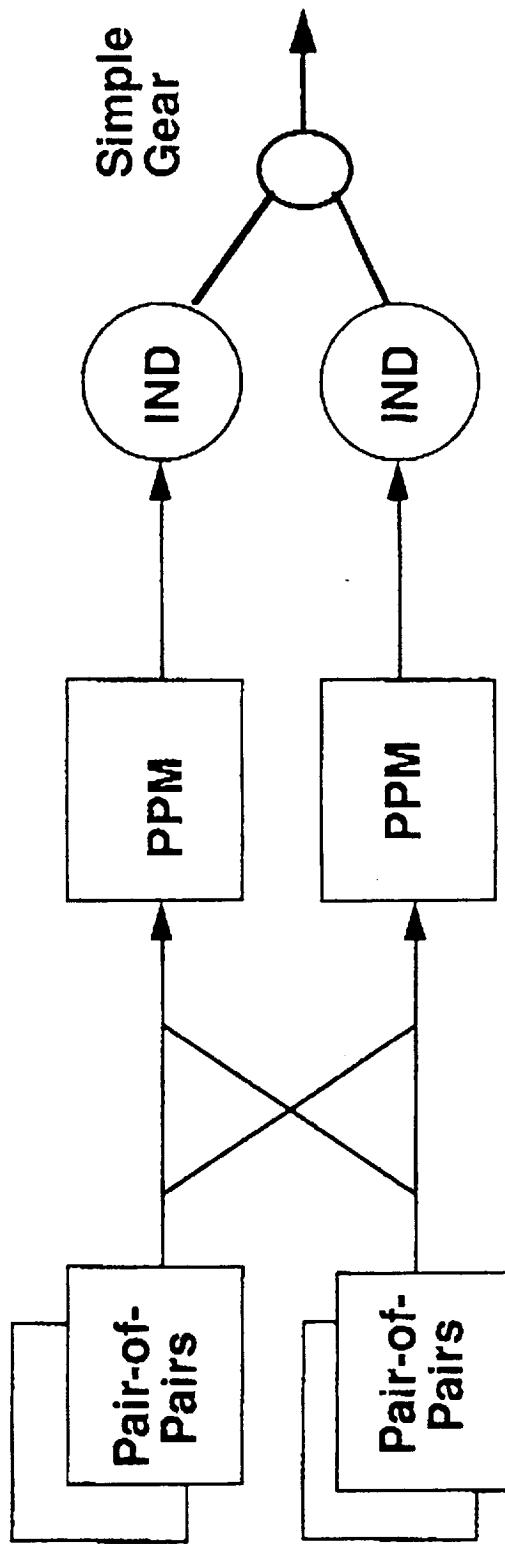
ARCS RACK

- 68020 Microprocessor
- FOC Algorithms
- Velocity Loop Closure
- DC//AC Transform

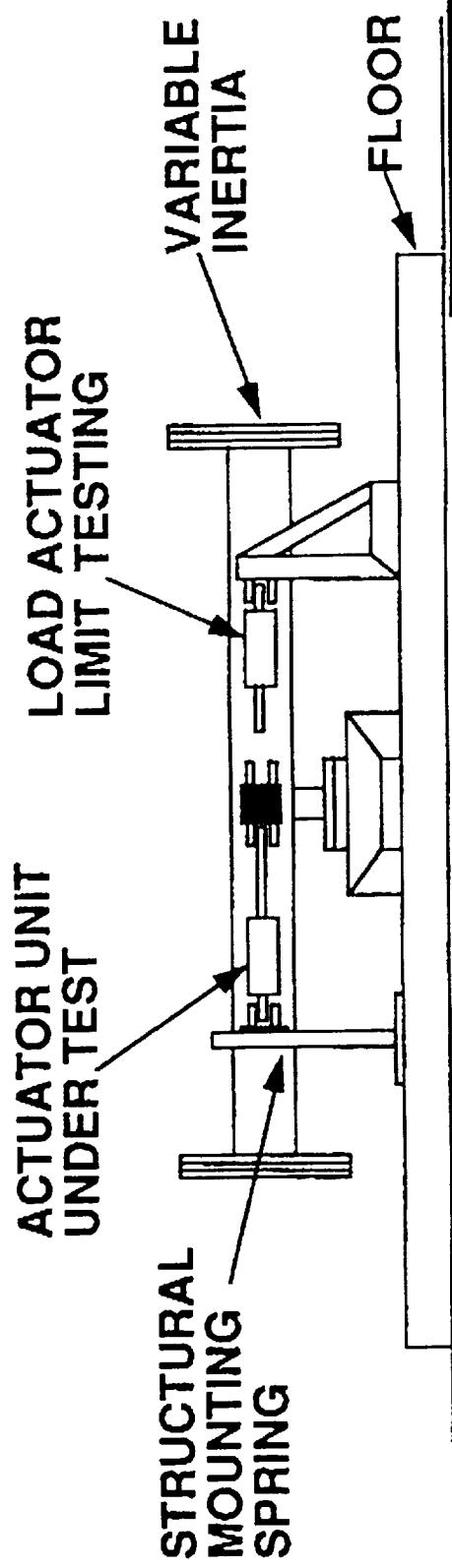
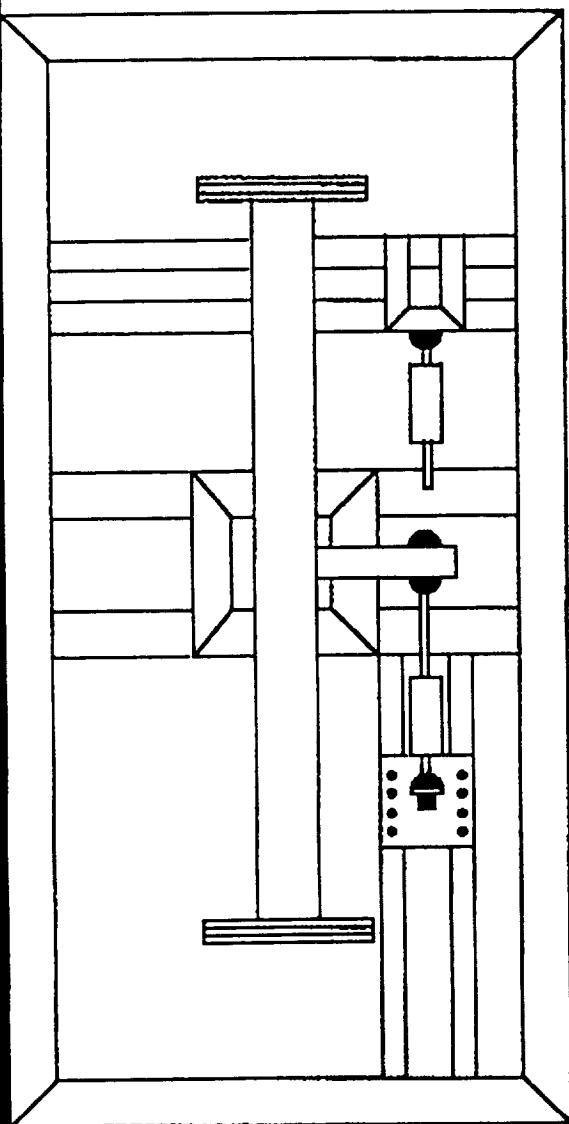


Fault-Tolerant System Test Bed Redundancy with Induction Motors

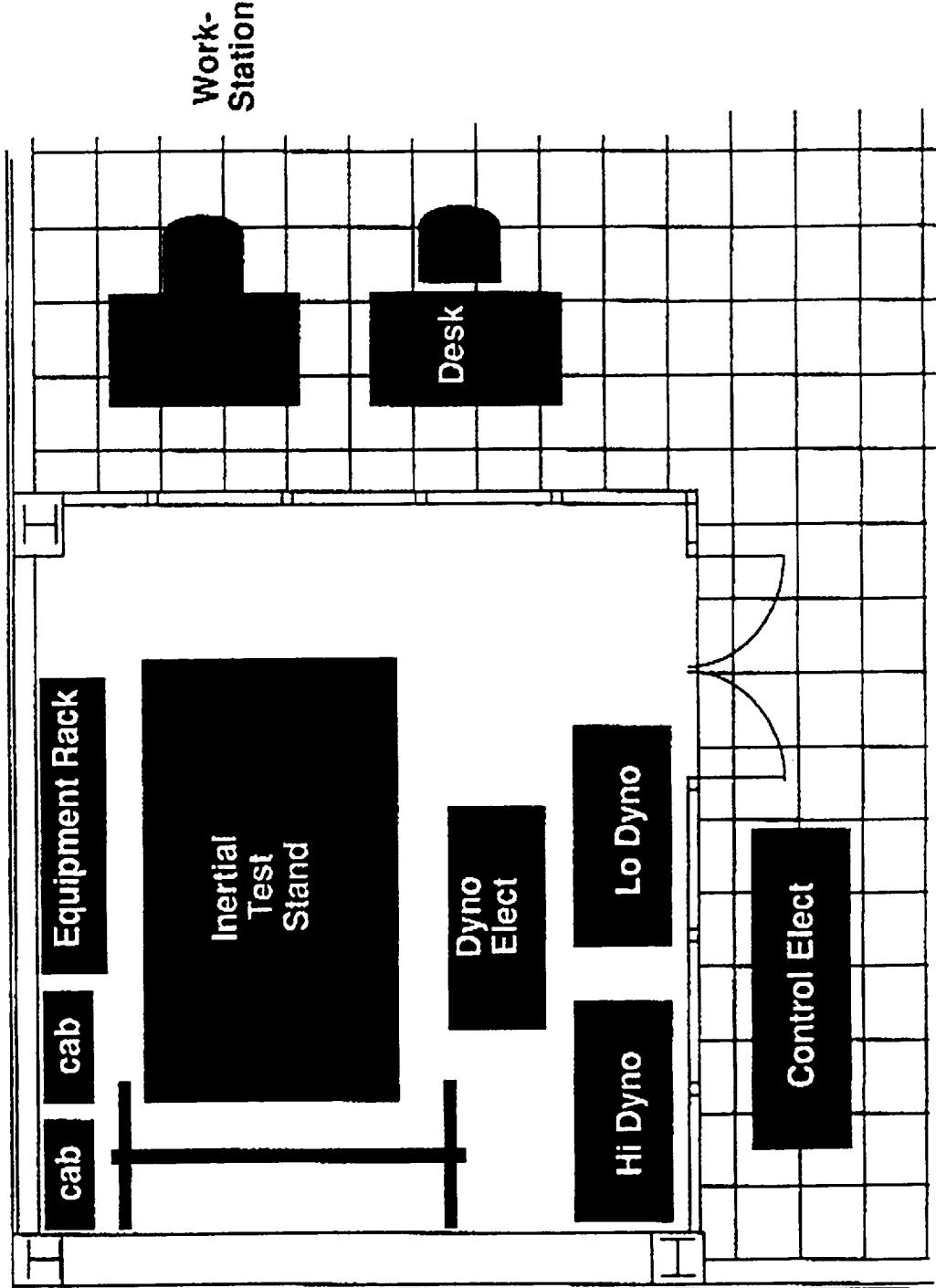
- All Software Approach Allows Fault Tolerant Embedded Computer Applications--such as Pair-of-Pairs or FTPP
- Motor Drive Can Be Either Pulse Placement or Pulse Width Modulation
- INDUCTION Motor Output Drives a Simple Gear Train



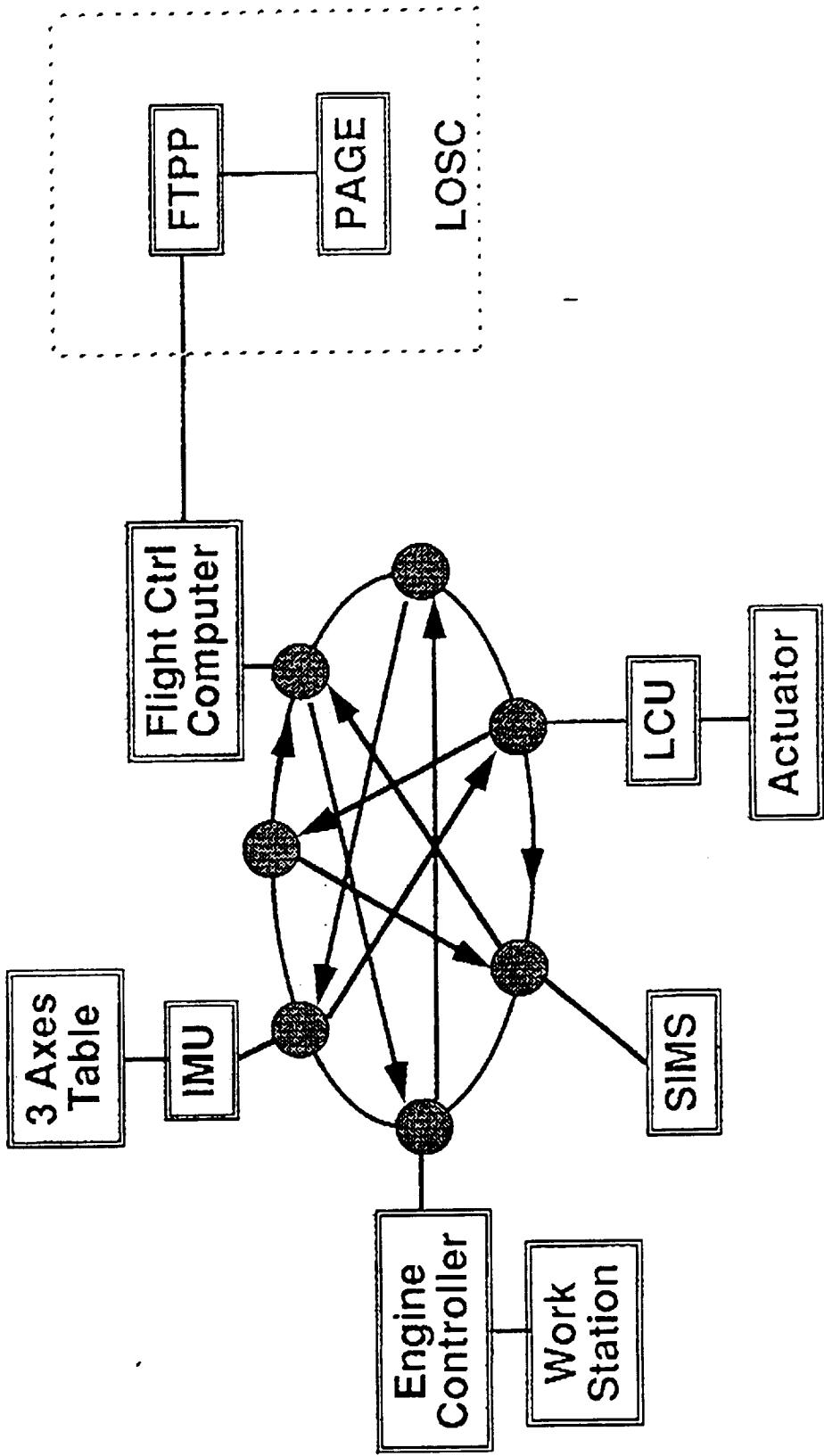
**Fault-Tolerant System Test Bed
Horizontal Pivot Pendulum Test Stand**



Fault-Tolerant System Test Bed Actuator Test Bed Layout



1993 FTA/HM Lab Demonstration Overview



092391_TIV_FTA/DW_SLB_B_2

Fault-Tolerant System Test Bed Summary

- **Flexible Test Bed**

- Systems
- Component
- Functional
- Performance
- **Multiple User**
 - Internal Research and Development
 - Airforce
 - NASA (multiple center)

FMEA'S AND FAILURES IN TEST

Rae Ann Weir / MSFC EP64
205-544-7146

During the time frame from November 1991 to the time of this workshop, 20 failures were recorded during testing of EMAs. Failures documented include those during the development and test of Marshall's in-house actuator and hardware brought in for test and demo. Failures were divided into two categories. The first category includes problems identified as areas which still require investigation. These are listed under Credible Failures/Problems.

Problems associated with EMI and grounding were seen with each piece of hardware brought into the lab. High power electronic problems accounted for the largest number of failures. This may be due to the fact that some development failures were documented for this presentation. It was soon discovered in the lab, with the rotational forces associated with these actuators, that more attention must be paid to the structural interfacing, at least for test purposes. The other category contains failures which include problems considered not to be applicable to a flight type actuator. These are the Noncredible Failures. For example, the motor failures which were documented occurred due to using off-the-shelf and not necessarily optimized hardware. This is not to say that a shorted motor would not be a credible failure, but failures of that nature have not been seen in test.

FAILURES IN TEST

20 Failures were recorded at Marshall during EMA testing activities. These include failures during development and test of Marshall's actuator and failures in hardware brought in for test and demo.

Credible Failures/Problems

EMI/Grounding
High Power Electronics
Testing/Vehicle Structural Interfacing

NON CREDIBLE FAILURES

Motor
Low power circuitry
Power

An attempt was made to determine a plausible fault tree for the EMA. Due to the different design philosophies, including EHAs, a single fault tree would probably exclude some of the failure modes of those designs I am less familiar with. What has been prepared are two levels of a fault tree with the first level being generic to all designs. Each actuation system may be broken down into sub-components: a power source, the control electronics, motor, actuation mechanism, sensors, and interfaces. While each actuator may have a different design philosophy, each utilizes some from of each of the sub-components listed. The next level is more particular to the design philosophy. This level includes a breakdown of each actuation sub-component into the elements which could cause a failure. The next step would be to identify each fault particular to an element. With each fault, a signature of the failure and a means of detecting it is important.

ELECTRICAL ACTUATION SYSTEM

FAULT TREE

- POWER
 - High Power Short Open Explosion
 - Avionics Power
- CONTROL ELECTRONICS
 - Low Power Sensors
 - High Power PWM
 - Current Bridge
 - Regeneration
 - Supporting Electronics
- MOTOR
 - Windings
 - Drive Shaft
 - Commutation Sensors
 - Magnets
- ACTUATOR
 - Gear Train
 - Roller/Ball Screw
- INTERFACES
 - Cabling
 - Connectors
 - Structural Attach Points
- SENSORS
 - Current
 - Rate
 - Position
 - Force

Task : Develop and implement a Vehicle Health Management (VHM) platform for Electromechanical Tvc actuation systems using actual hardware and vehicle simulations in the loop.

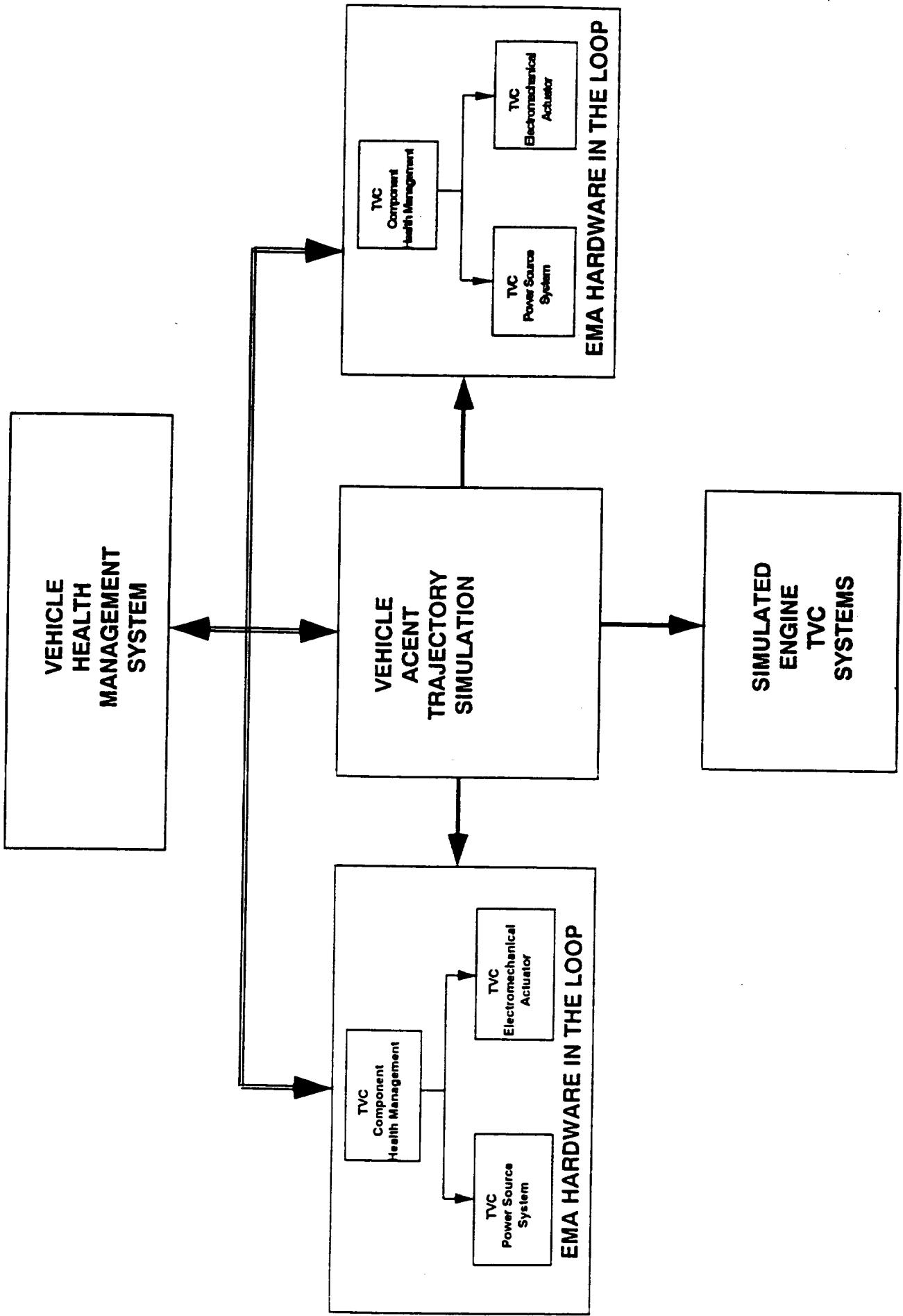
MSFC is proposing to upgrade existing facilities in order to implement a platform for the testing and development of Vehicle Health Management (VHM) for electromechanical actuators. The proposed platform will incorporate hardware, including power sources and vehicle as well as hardware simulation. The first step will be to determine the requirements and tools to implement a VHM hierarchy, working with a bottoms up philosophy. From there, each level of technology will be demonstrated until a full actuation system VHM level is attained. This platform will be used by MSFC to investigate VHM algorithms, redundancy, etc. It is our hope that NASA and Industry will take advantage of these facilities for further development of EMAs.

HARDWARE DEMONSTRATION OF

VHM SYSTEM

- Establish Requirements, Sensor Suites, and Algorithms for VHM hierarchy
 - BIT
 - Component Level
 - System Level
- Implement VHM Platform with hardware in the loop
 - Component Level Health Management
 - Vehicle Simulation
 - System Level VHM
- Demonstrations
 - TVC EMA System
 - (MSFC, Moog, Honeywell, Allied Signal, Boeing, GD)
 - Apply similar techniques to EMA Valve Actuation System

MSFC EMA\TVC PLATFORM FOR VEHICLE HEALTH MANAGEMENT DEMONSTRATIONS



FACILITIES, HARDWARE AND SUPPORT

- Component Development Laboratory (Bldg. 4656)
Two inertia load simulators, soon to be equipped with programmable force generators.
- Prototype EMA hardware
- In-house support may be obtained from EB and ED laboratories
- Contractor support will be required for software development.
- Contractors will be invited to use test platform.

SESSION XII

ELA PROTOTYPE DESIGN & TEST RESULTS

MOOG INC.

MISSILE SYSTEMS DIVISION

38 HP ELECTROMECHANICAL ACTUATOR

IR&D PROGRAM OVERVIEW

NASA
ELECTRICAL ACTUATION
TECHNOLOGY BRIDGING
WORKSHOP

SEPTEMBER 29 - OCTOBER 1, 1992

INTRODUCTION

- Objectives of Moog's 38 HP EMA IR&D PROGRAM
- Design Criteria
- Hardware Description
- Test Results

MOOG

Missile Systems Division

— OBJECTIVES —

- Demonstrate EMA Performance for 30-50 HP TVC Application
- Design, Build, and Test Single String EMA Hardware
- Compare to Known Hydraulic System Performance
- Baseline SSME TVC Requirements
- Design Actuator To Accommodate
 - Ballscrew
 - Rollerscrew

PROGRAM PLAN

- Initiated Moog Funded IR&D Activity 1990

- Demonstrate Single String EMA
- No Effort to Optimize Weight
- Include Dual Motor Capability
- Utilize "Bolt-On" Motors to Permit Motor Comparison
- Designed to Handle Start-up Transient Loads Structurally
- Controller not Flight Packaged

- Future Considerations

- Redundancy
- Impact Loads
- Motor Selection
- Power Source
 - Flight Weight Controller and Actuator

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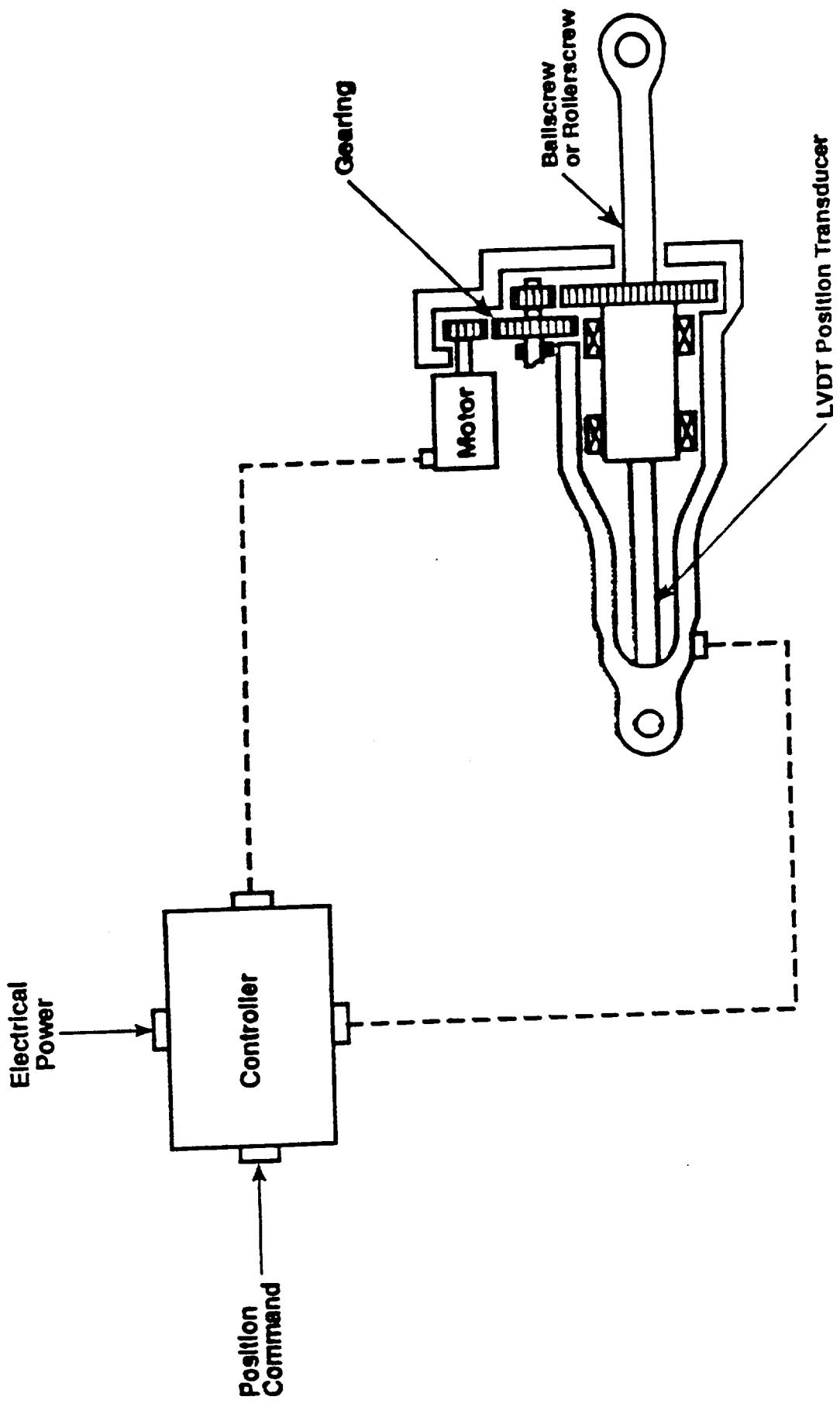
Missile Systems Division

DESIGN CRITERIA

(Based on SSME TVC Requirements)

Supply Voltage	270 VDC
Output Travel	± 5.5 in.
Rated Power	38 HP
	48,000 lb.
	5.2 in/sec.
Impulse Load Capacity	100,000 lb.
Frequency Response	< 80 deg. phase at 3 Hz
	at $\pm 2\%$ Command
Acceleration	60 in/sec^2
Pin to Pin Length	47 in.
	at Mid stroke

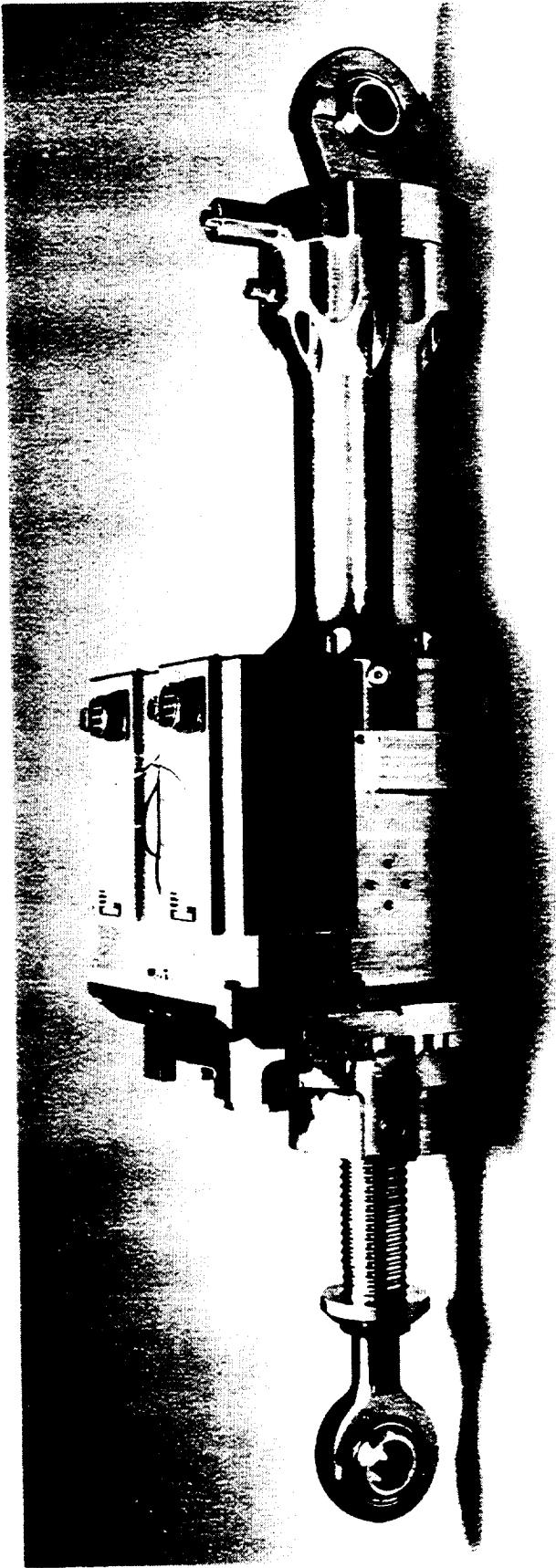
MOOG IR&D EMA TVC ACTUATION SYSTEM



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Missile Systems Division

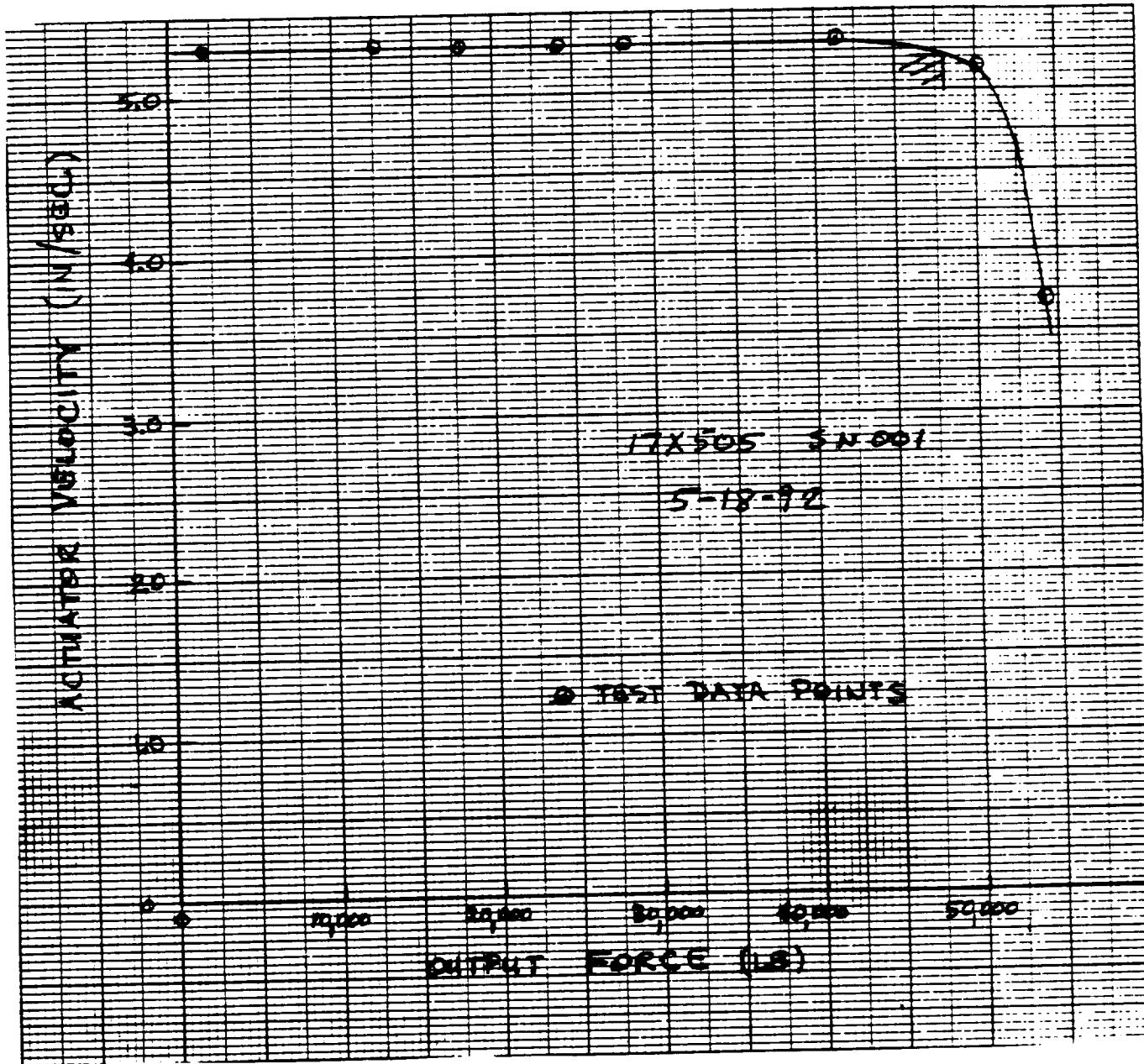
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OUTPUT TRAVEL	±5.5 IN	RATED POWER	38 HP
STALL FORCE	48,000 LB	-OUTPUT FORCE	48,000 LB
MAXIMUM IMPULSE LOAD	100,000 LB	-OUTPUT VELOCITY	5.2 IN/SEC
ACCELERATION	60 IN/SEC ²	DUTY CYCLE	10 MIN
		-AVERAGE LOAD	15,000 LBS
		SUPPLY VOLTAGE	270 VDC

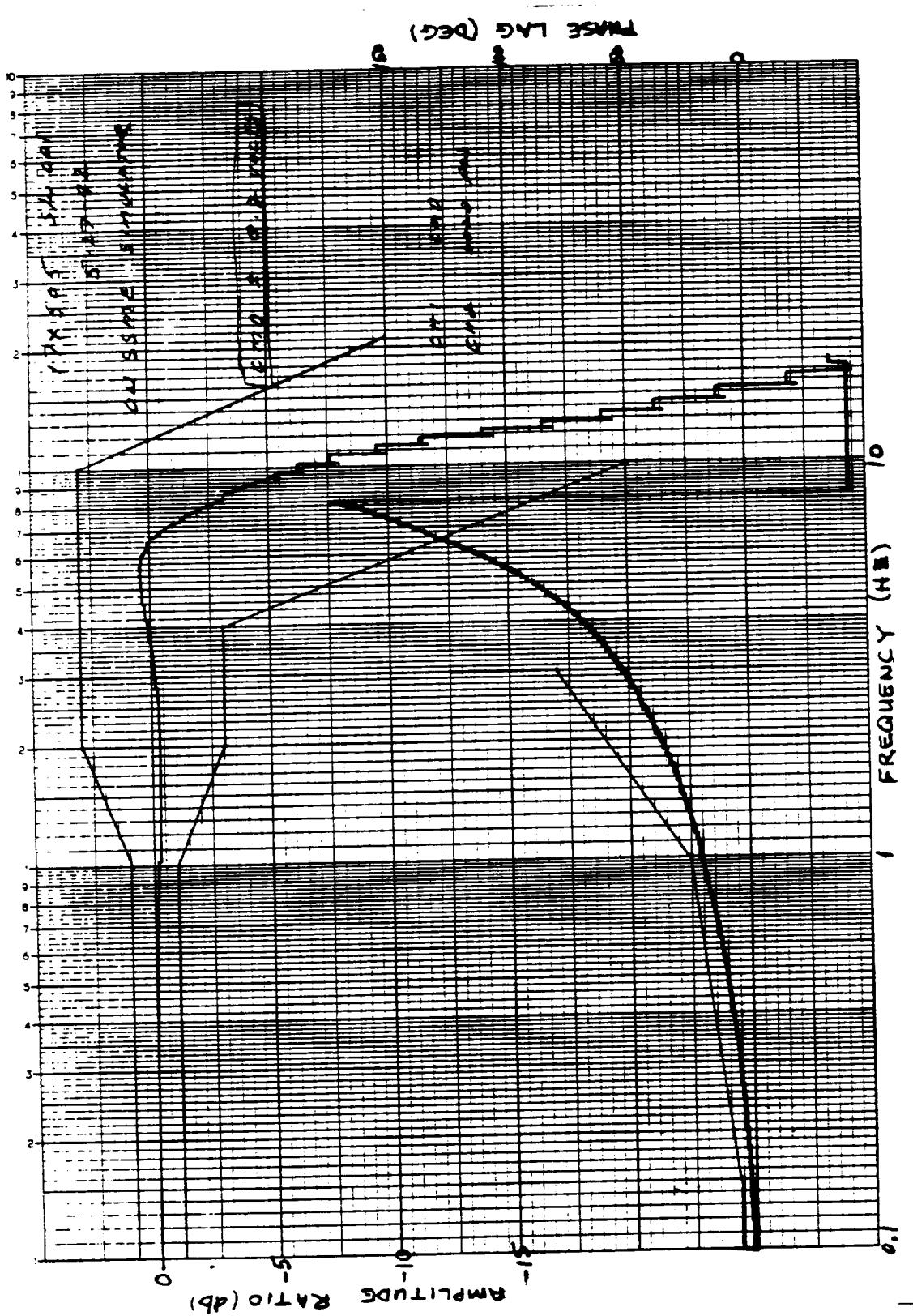
Electromechanical Actuator Dual Torque - Summed Motors

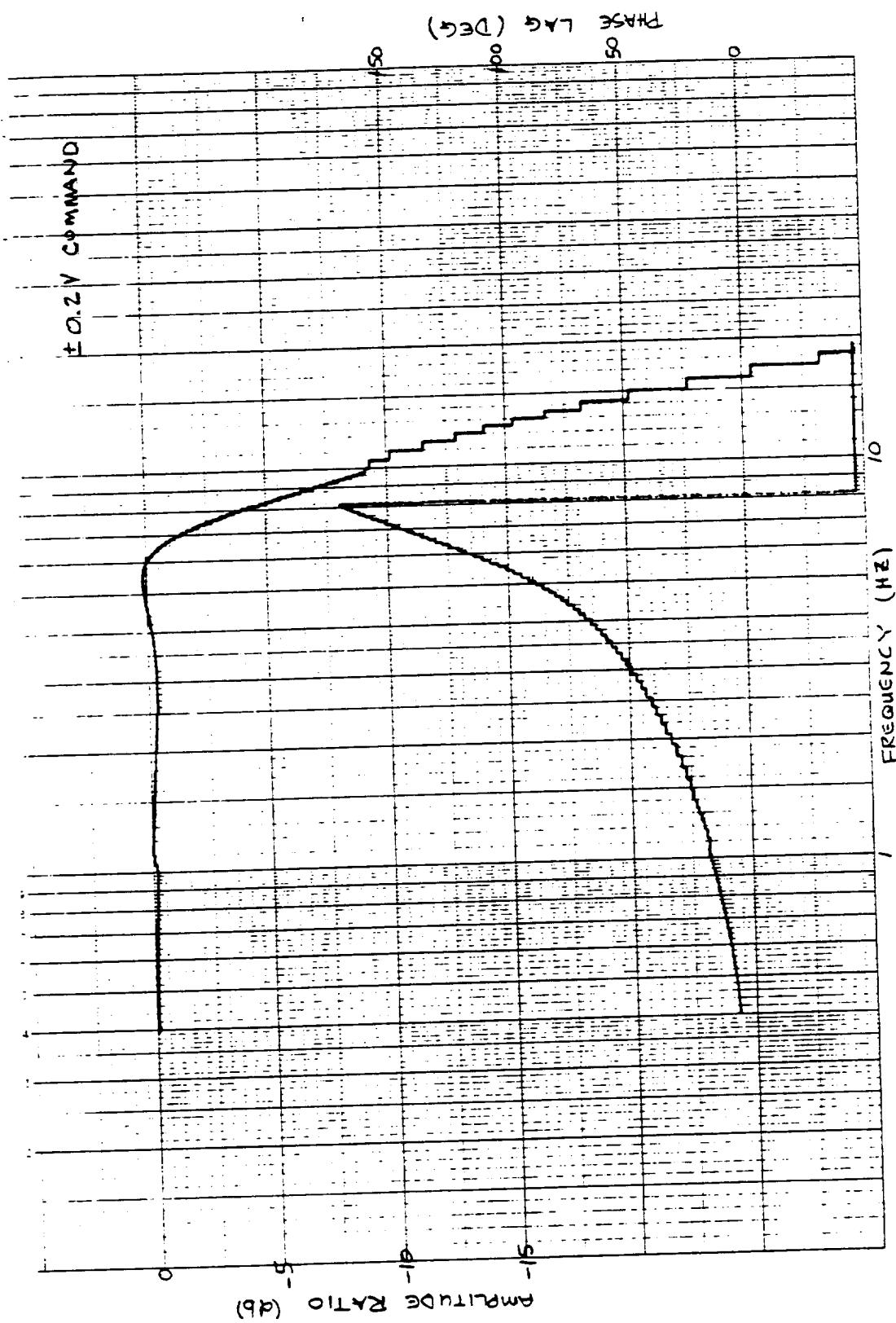
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FORCE - VELOCITY TEST DATA
MOOG 38 HP EM TVC SYSTEM
ON SSME TEST FIXTURE

MOOG

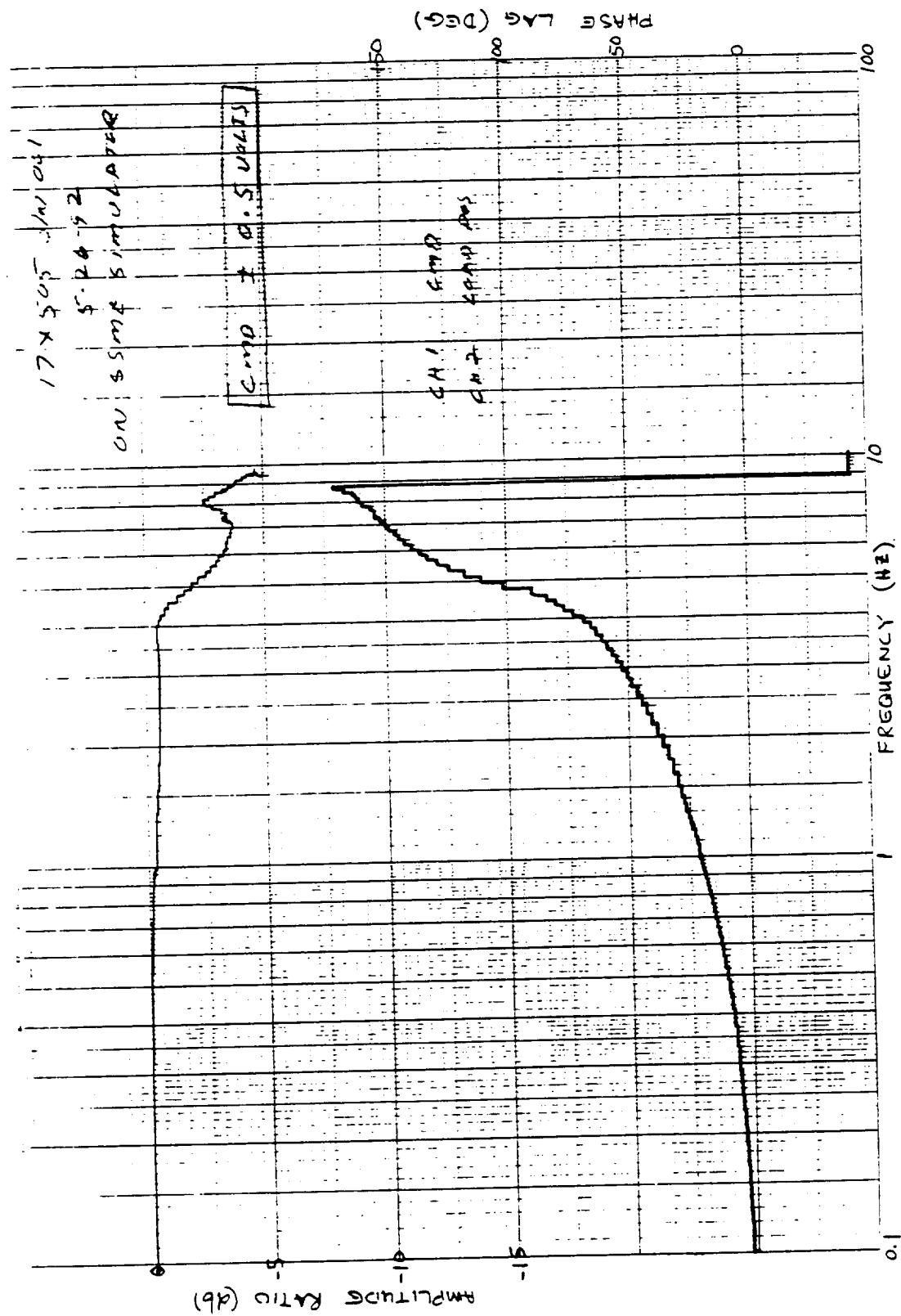




SIMULATION DATA
LOAD POSITION FREQUENCY RESPONSE ($\pm 2\%$)
MOOG 38HP EM TVC ACTUATION SYSTEM WITH SSME LOAD

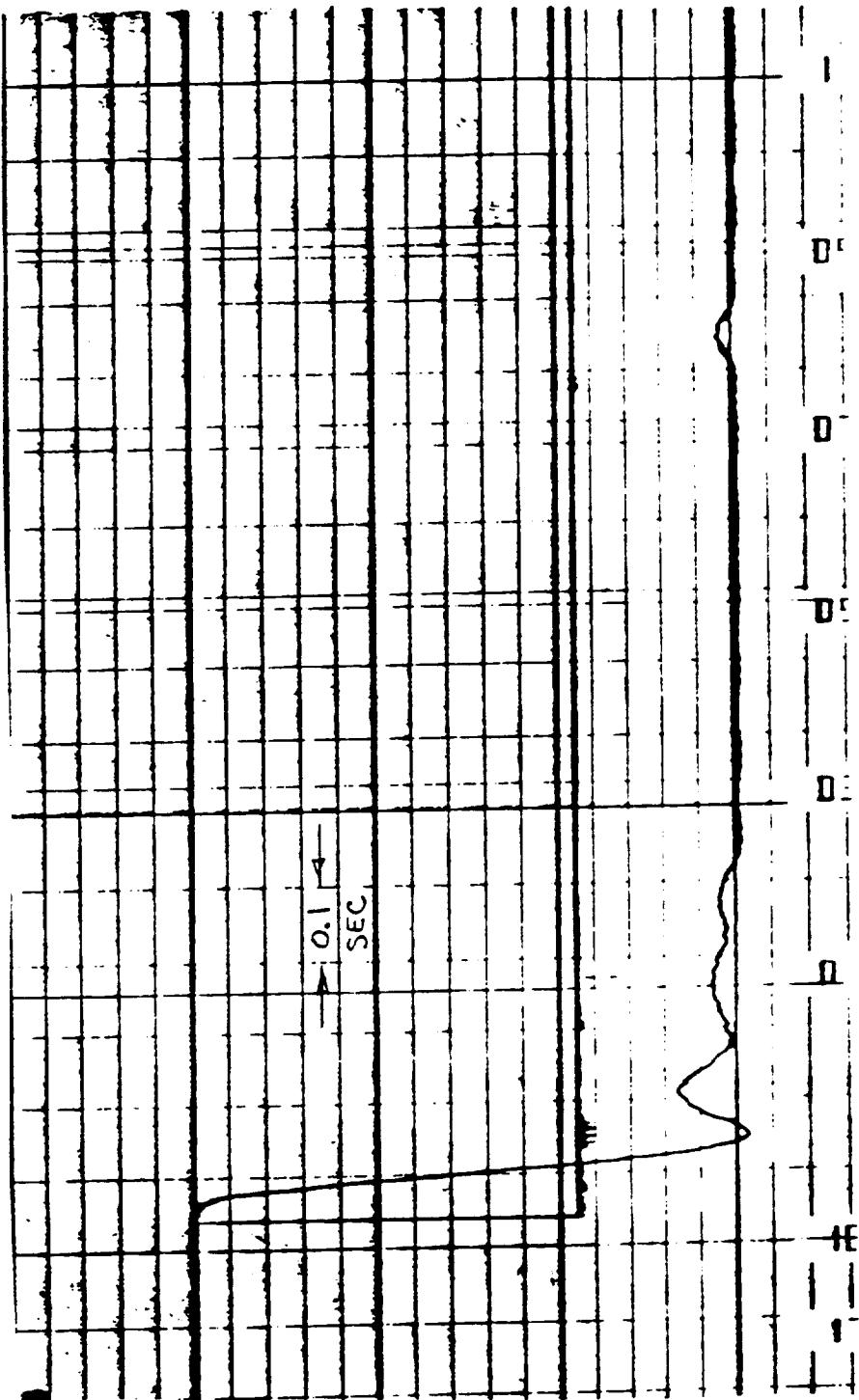
MOOG

MOOG



TEST DATA
LOAD POSITION FREQUENCY RESPONSE ($\pm 5\%$ COMMAND)
MOOG 38HP EM TVC ACTUATION SYSTEM ON SSME SIMULATOR

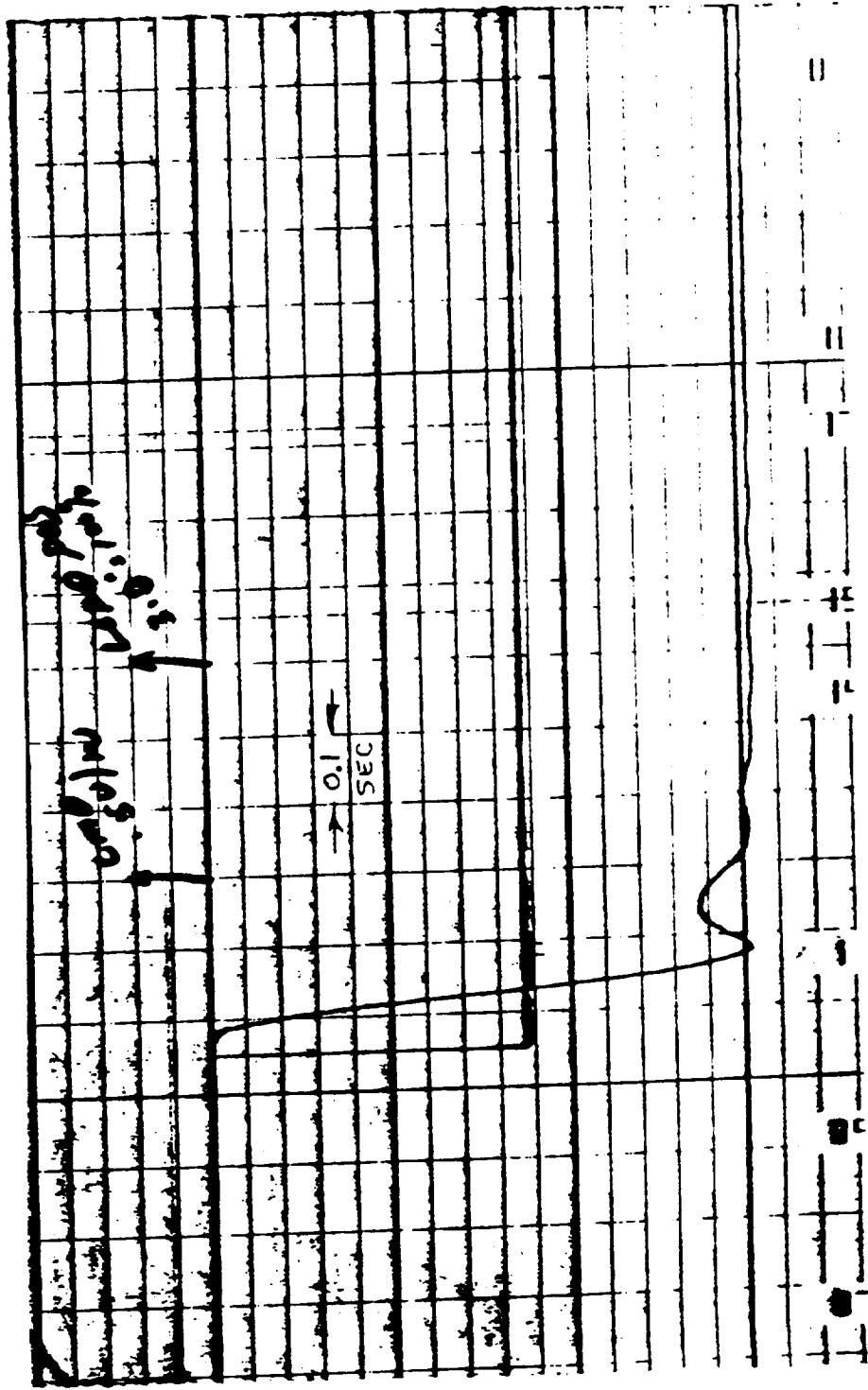
17E505 S/N 001
7-17-92



0.25 IN STEP RESPONSE
ON SSME SIMULATOR
(LOAD POSITION)

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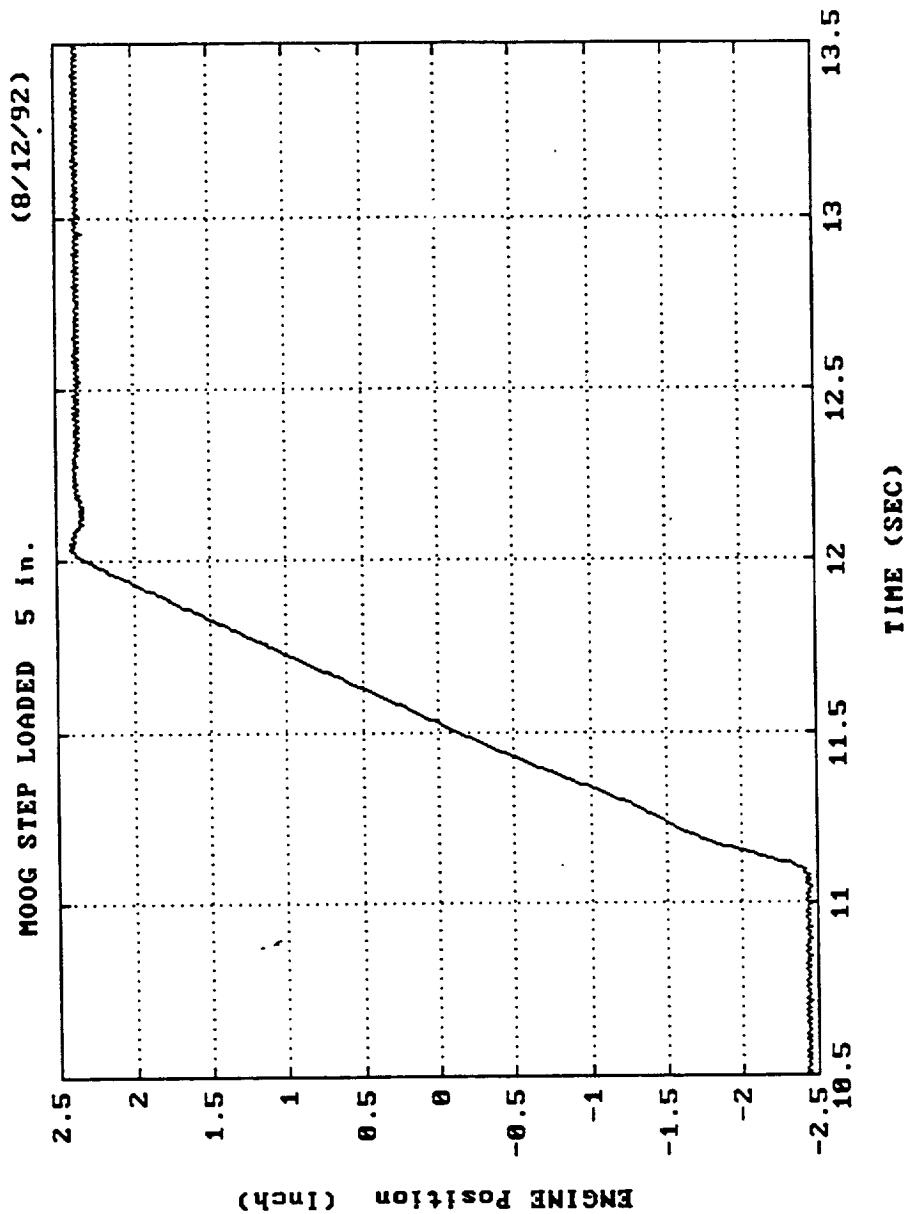
17E505 S/N 1
7-17-92



0.5 IN STEP RESPONSE
ON SSME SIMULATOR
(LOAD POSITION)

MOOG ACTUATOR ON MSFE SIMULATE

5 STEP RESPONSE



EM TVC ACTUATOR TEST DATA

BALLSCREW ACTUATOR	ROLLERSCREW ACTUATOR
Mechanical Efficiency	
at Stall	70%
at Power Point	78%
Friction	1650 lbs.
Stiffness (Locked Rotor)	
Midstroke	1.47×10^6 lb/in
Extend	1.34×10^6 lb/in
Acceleration	
One Motor	1.5×10^6 lb/in
Two Motors (One Driving)	1.38×10^6 lb/in

Mechanical Efficiency

at Stall

at Power Point

70%
78%

Friction

1650 lbs.

Stiffness (Locked Rotor)

Midstroke

Extend

1.47×10^6 lb/in
 1.34×10^6 lb/in

Acceleration

One Motor

Two Motors (One Driving)

1.30 in/sec^2
 65 in/sec^2

PERFORMANCE RESULTS OF MOOG **BRUSHLESS EM TVC SYSTEM**

<u>Parameter</u>	<u>SSME Spec</u>	<u>Test Results</u>
Frequency Response ($\pm 2\%$ Command)	< 25 deg. Phase at 1 Hz < 80 deg. Phase at 3 Hz	Meets Requirement
Rated Power Point		Meets Requirement
Output Force	48,000 lbs.	
Output Velocity	5.2 in/sec.	
Output Travel	± 5.5 in.	Meets Requirement
Actuator Stiffness	790,000 lb/in.	Meets Requirement

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Missile Systems Division

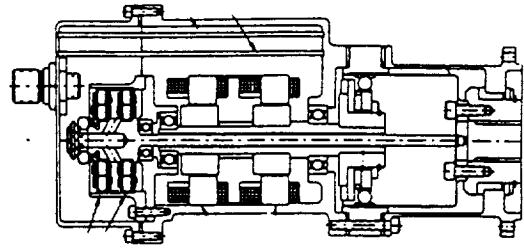
**ELECTROMECHANICAL PROPELLANT
CONTROL ACTUATORS**

MARTHA B. CASH

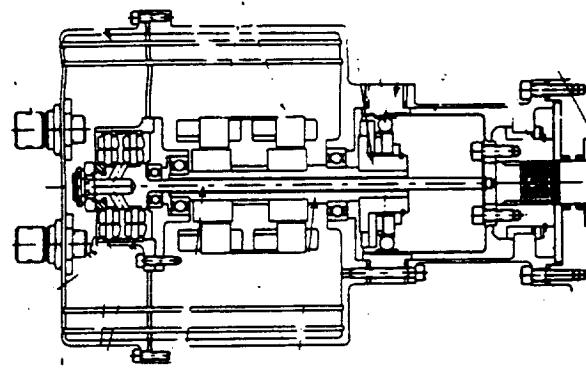
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OCTOBER 1, 1992

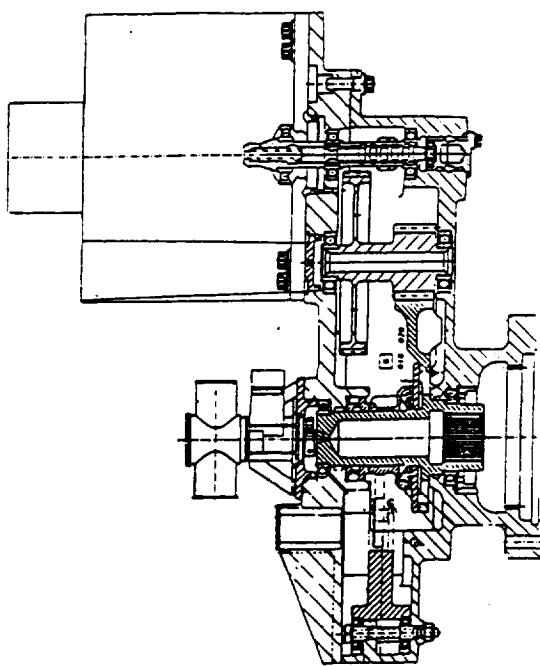
**ELECTROMECHANICAL PROPELLANT
CONTROL ACTUATORS**



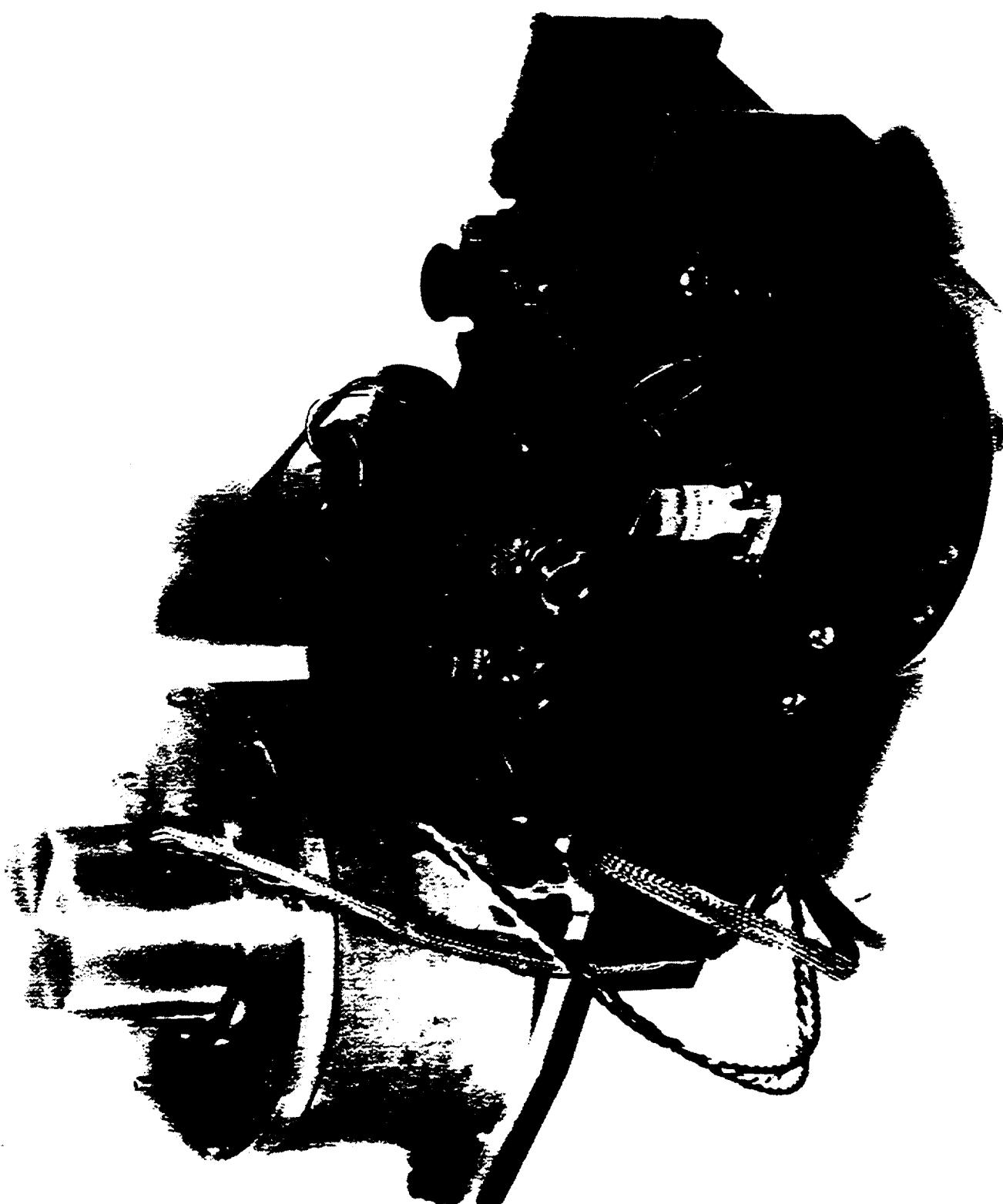
IN-HOUSE SIMPLEX



AEROJET



HR TEXTRON



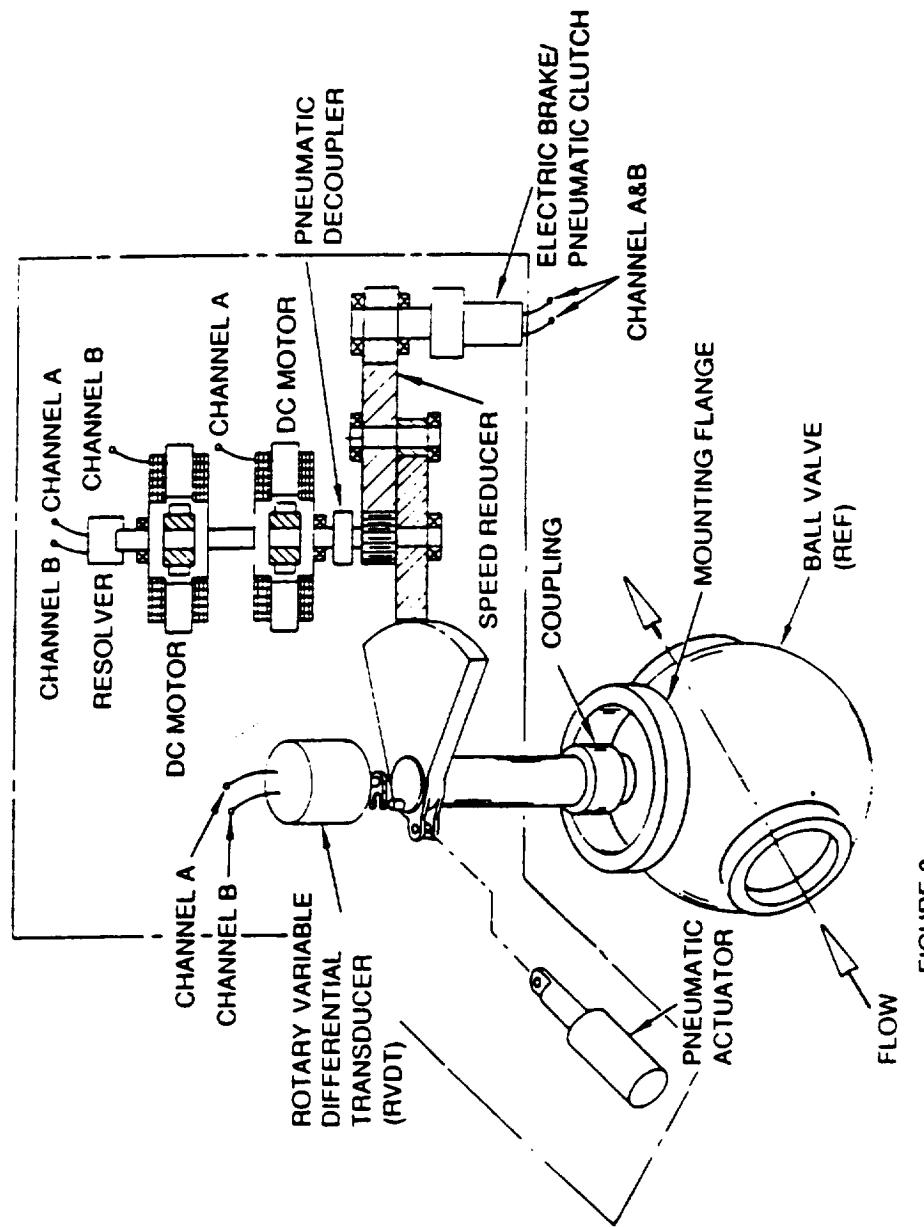


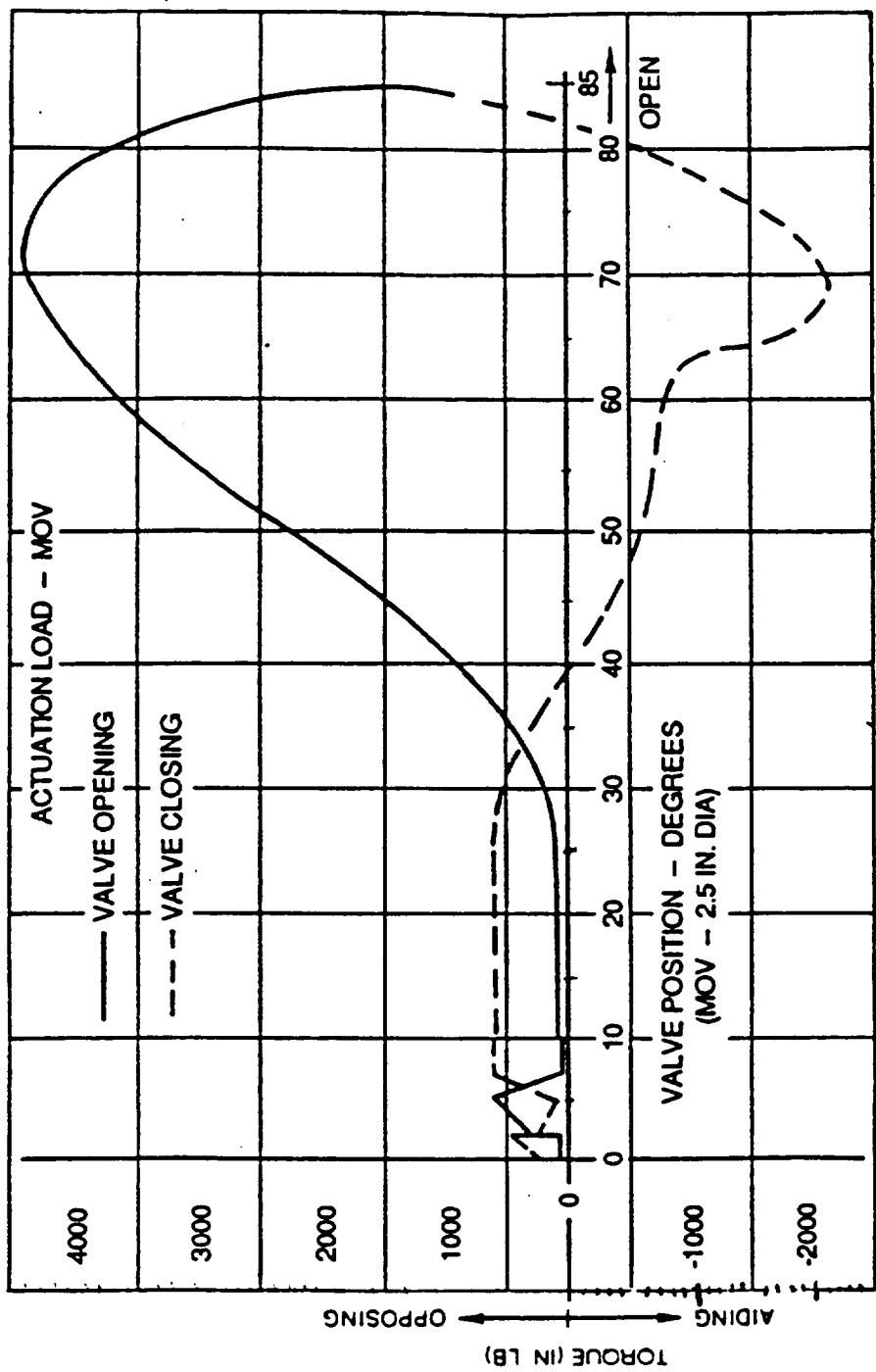
FIGURE 3
DUAL MOTORS WITH SINGLE SHAFT CONCEPT

DESIGN REQUIREMENTS

DESIGN REQUIREMENT	VALUE
VALVE OPEN/CLOSE TRAVEL	84° 45' - 85° 30'
VALVE POSITION ACCURACY	± 3% OF 85° (MAX.) ± 1.3% OF TOTAL TRAVEL FROM 50-60% OPEN
VALVE RATE (DEG./SEC.)	360 (MAX.)
ATMOSPHERIC PRESSURE (TORR)	SEA LEVEL TO 1×10^7
AMBIENT OPERATING TEMP. (°F)	-50 TO 130
ACTUATOR CONTROLLER AMBIENT OPERATING TEMP. (°F)	40 TO 110
ACTUATOR NON-OPERATING TEMP. (°F) FOR 2 HRS.	-200 TO 10
LIFE (HRS)	8
LOAD (MAX.) (IN.-LB.)	4500
WEIGHT (LBS.)	70

DESIGN PARAMETERS

<u>DESIGN PARAMETERS</u>	<u>VALUE</u>
RVDT ERROR BAND	2% OF THE FULL SCALE
RVDT EXCITATION	20 VOLTS, PEAK TO PEAK AT 2000 Hz
GEAR RATIO	85:1
CLOSED LOOP THRESHOLD UNDER LOADING	0.025% OF FULL TRAVEL
MAX. CURRENT (AMP.)	40
LINE BUS VOLTAGE (VOLT)	270
VALVE RATE (DEG./SEC.)	245 (NOMINAL)
RESOLVER EXCITATION	4 VOLTS RMS PEAK TO PEAK AT 10 kHz
FREQUENCY RESPONSE	-3 db AT 10 Hz (NOMINAL) 90° PHASE LAG AT 10 Hz (MAX.)
ACTUATOR LOADING (IN.-LB.)	AS DEFINED IN FIGURE 1
HELIUM PRESSURE (PSI)	700 TO 800
PNEUMATIC SHUTDOWN VALVE CLOSING TIME (FROM FULL OPEN)(SEC.)	1.4 TO 3.1



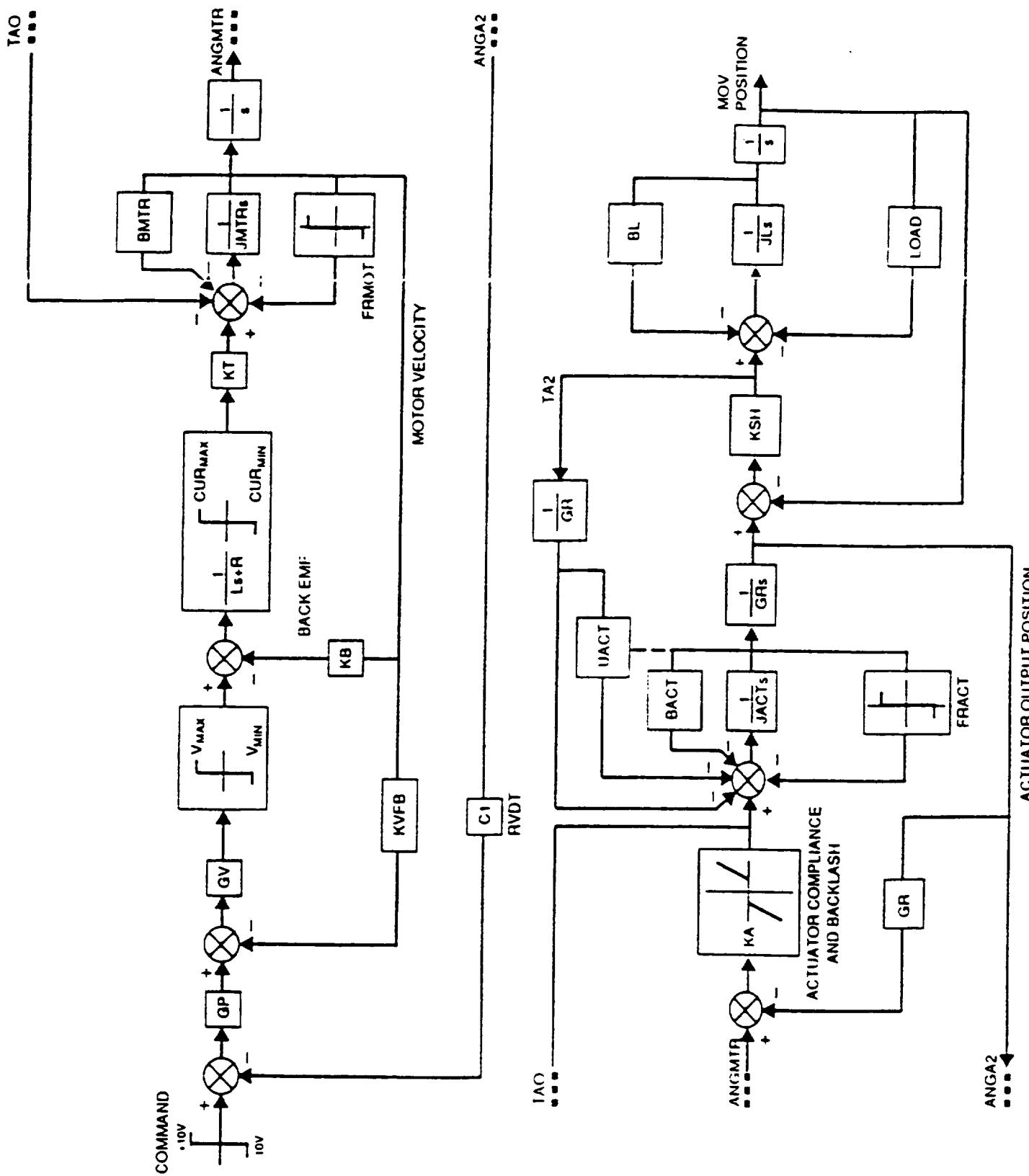
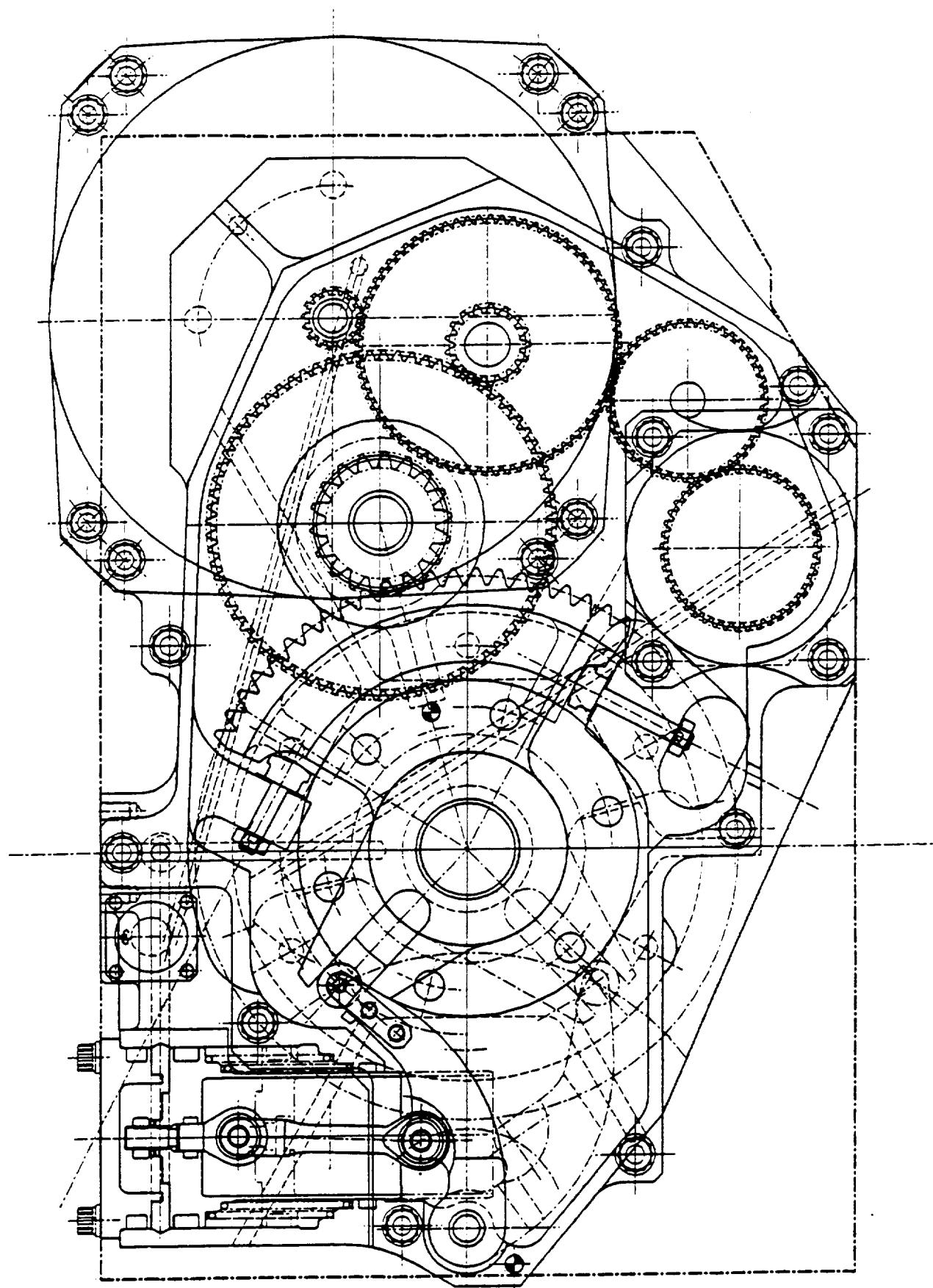
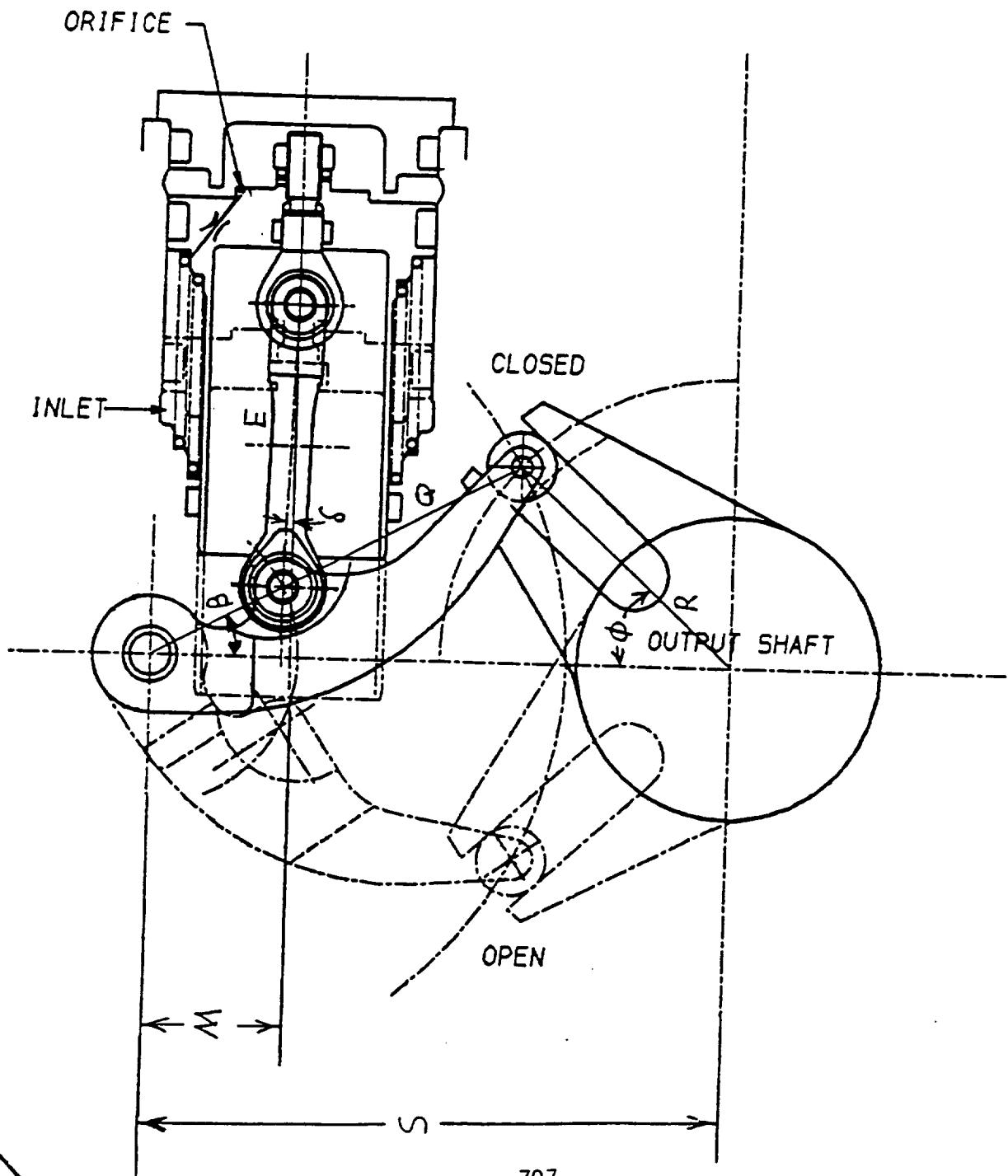
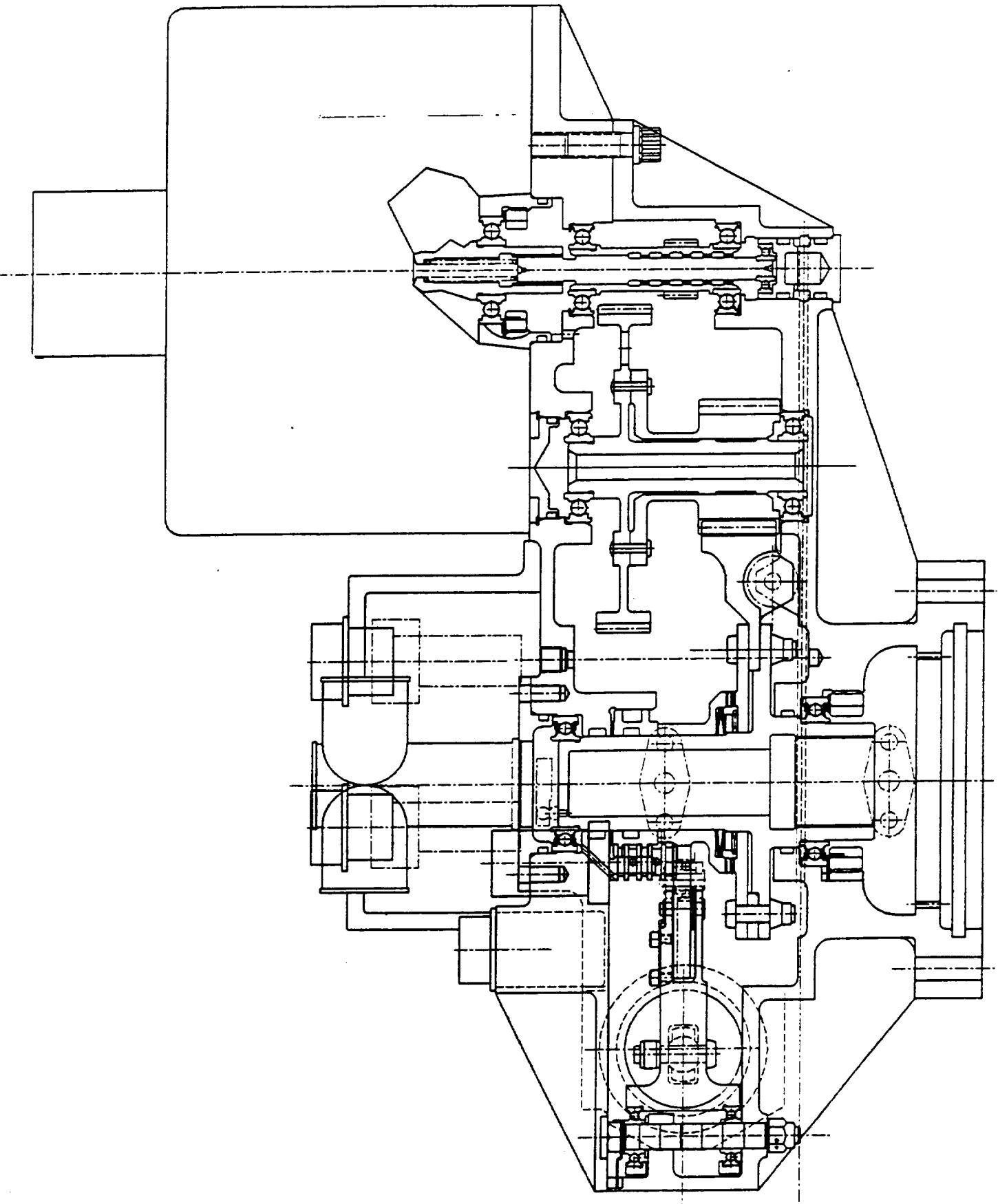


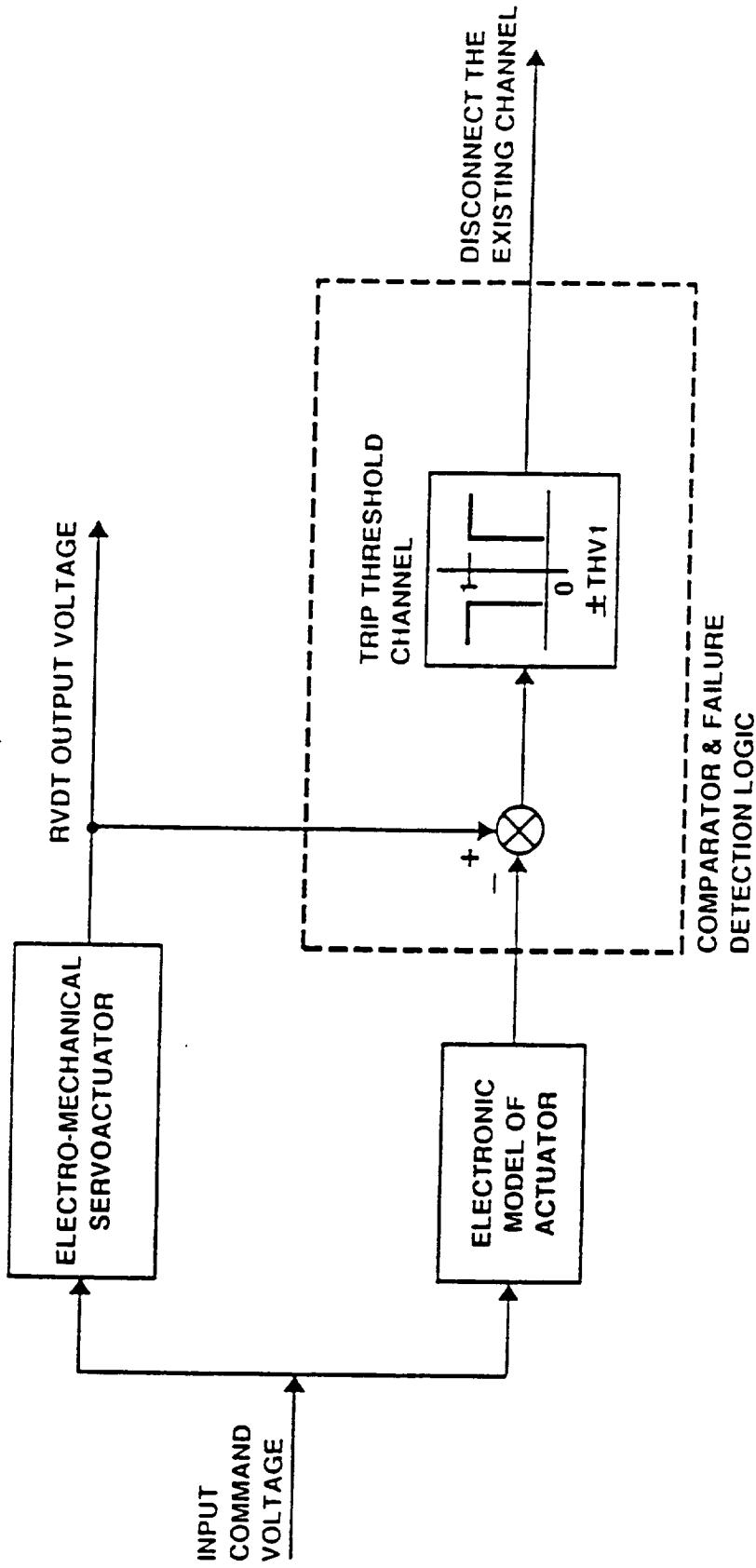
Figure 9



MOV PNEUMATIC SHUTDOWN ACTUATOR







FAILURE DETECTION BLOCK DIAGRAM

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EXTENDED LOCKUP TEST (ATP para. 4.11.4)

P/N X41009110

Date SEP 15 1992Operator TRT 148Comments LoadedS/N X001

Item	Required	Actual
Load Direction Sense	CCW	CCW
Load	MOVA	MOVA
Reduced Power	Minimum	MIN
Encoder Reading (Start of Lockup)	1894 ± 2 bits	1894
Encoder Reading After 10 Min Lockup	//////////	1846
Total Drift After 10 Min Lockup	82 bits max	48
Load Direction Sense	Active	ACTIVE
MOV Load	Remove	REMOVED

PAGE NO.

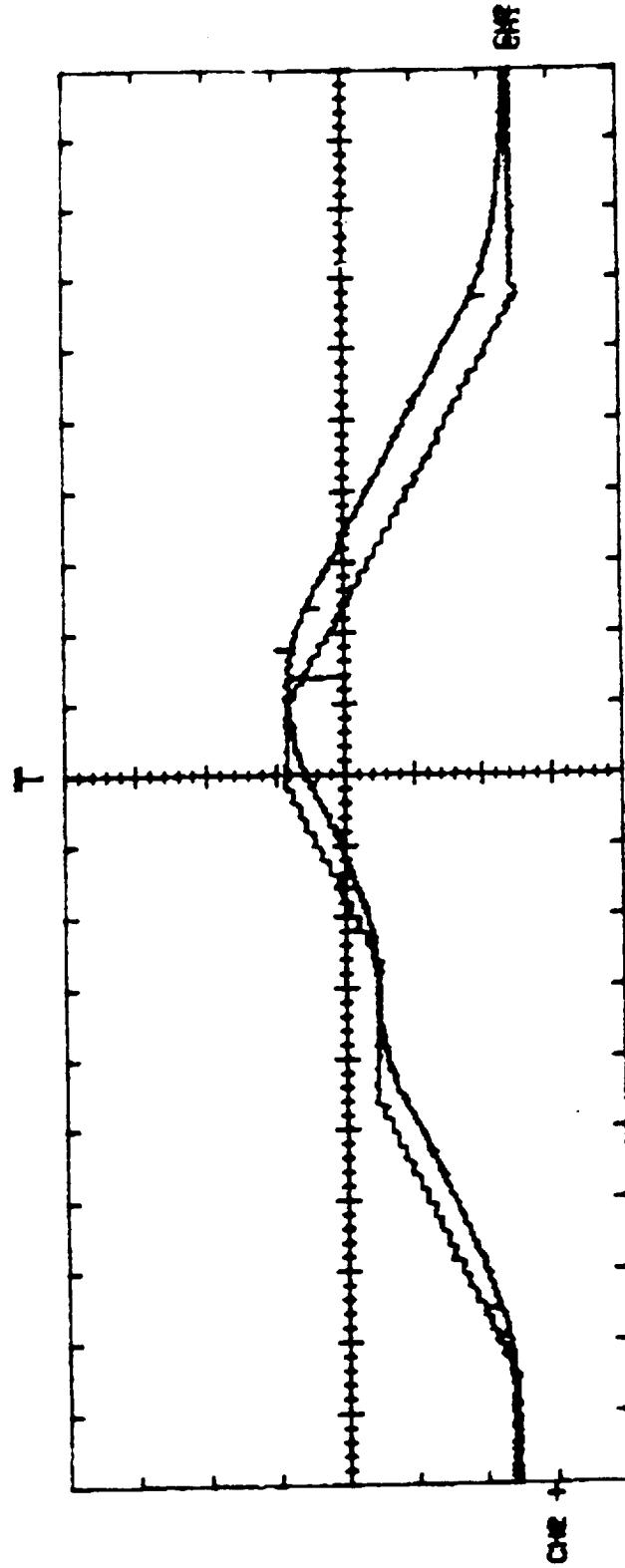
53

PAGE REVISION LETTER

TEK/2430

CH2 C 2 V /div
CH2 DC 2 V /div
CH2 NORMAL
CH2 NORMAL

100mSEC/div
100mSEC/div



COMMAND AND TRACKING
Lunar Rendezvous Panel

P/N X41009110
S/N X001
SEP 16 1992 (RT)
W40

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A SUBSIDIARY OF TEXTRON INC.25200 WEST RYE CANYON ROAD • VALENCIA, CALIFORNIA 91355
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ACTUATOR SLEW RATE (ATP Para 4.9)

(Page 1 of 3)

P/N X41009110

Date SEP 15 1992

Operator

Serial No. X 001Comments: Loaded

	Shaft Position	Input Signal	MFVA Load	Slew Rate %/Sec			
Required	Open-Close-Open	+30 ± 1 mA	MOVA Load Fig. 11	143 min.			
	Open-Close-Close			340 max.			
(Failsafe Switch only Energized)	Close to Open	+30	Data Fig. 1	161 $\frac{2}{3}$ %/s			
	Open to Close	-30	Data Fig. 2	172 $\frac{2}{3}$ %/s			
(Failop and Failsafe Switch Energized)	Reversal to Closed	+30	Data Fig. 3	152 $\frac{2}{3}$ %/s			
	Reversal to Opened	-30	Data Fig. 4	157 $\frac{2}{3}$ %/s			

PAGE NO.

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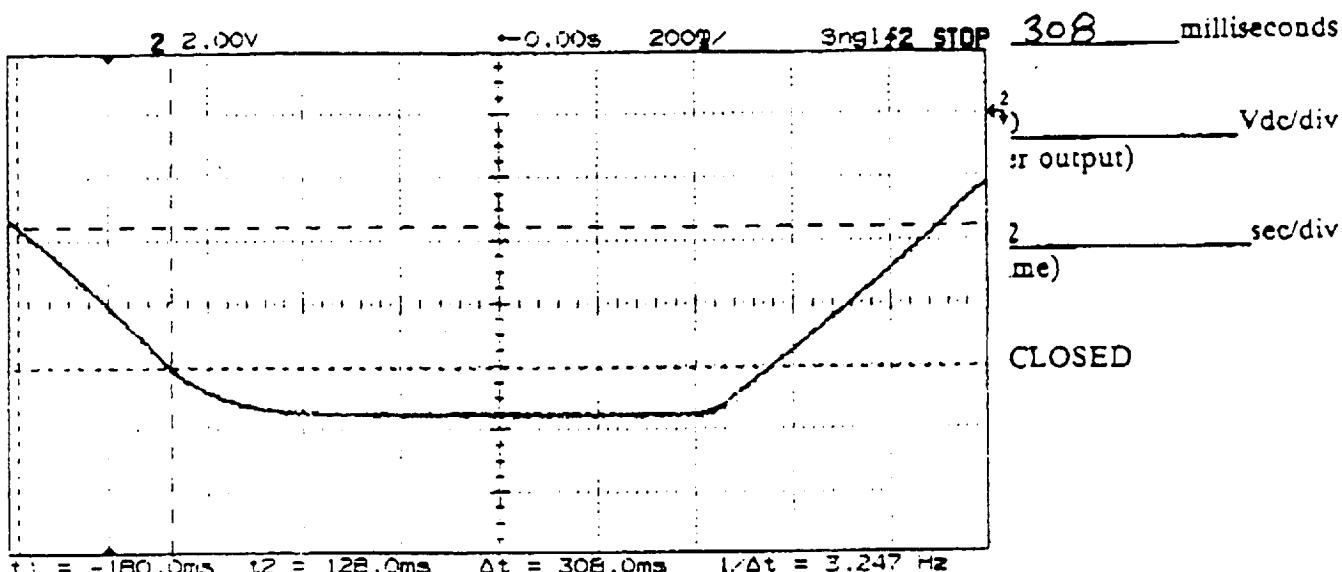
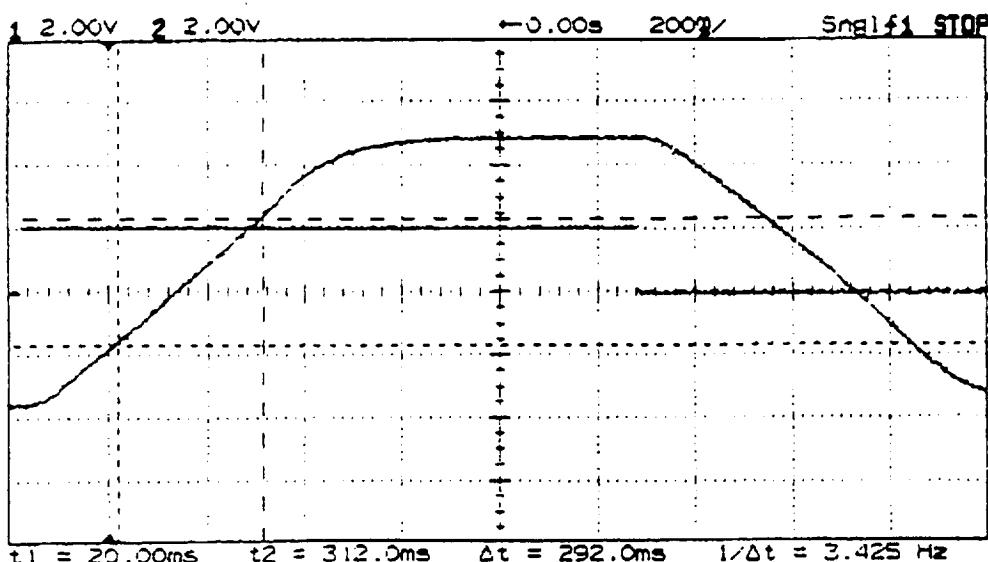
ACTUATOR SLEW RATE (ATP Para 4.9)

(Page 2 of 3)

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SN X001

SEP 15 1992



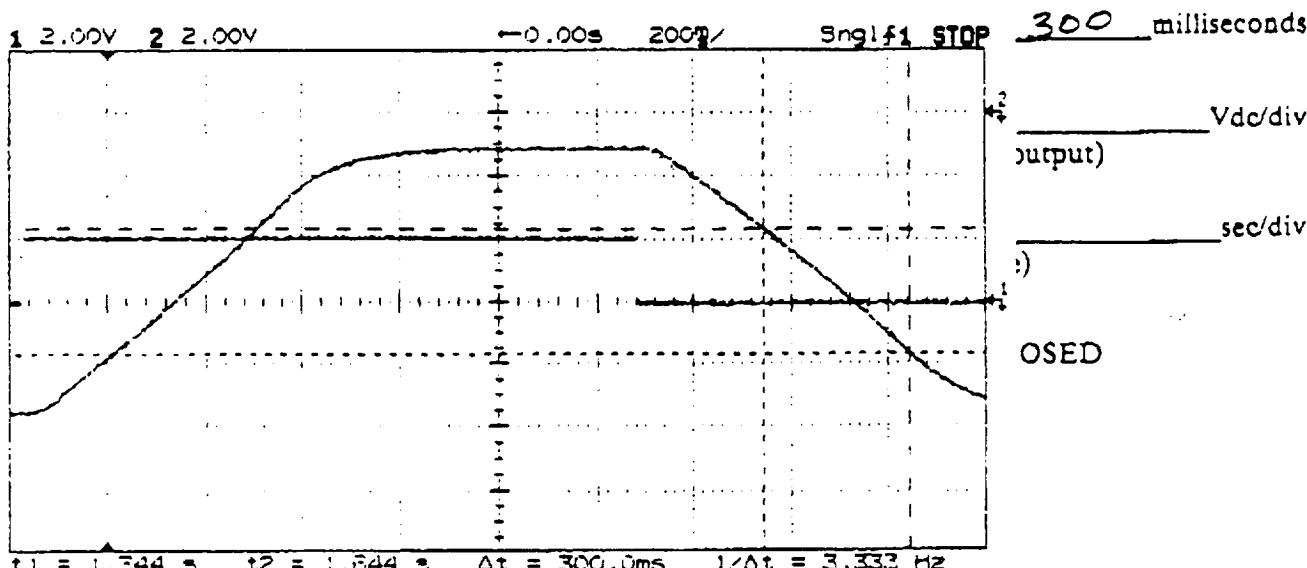
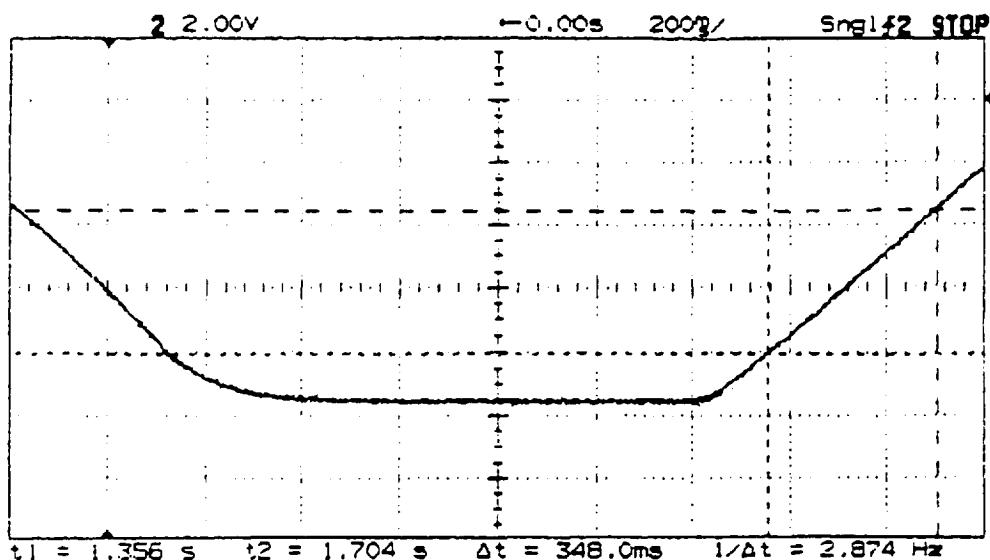
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PAGE REVISION LETTER

ACTUATOR SLEW RATE (ATP Para 4.9)

(Page 3 of 3)

SEP 15 1992

P/N X41009110 S/N X001

HRT
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PAGE REVISION LETTER



HR TEXTRON INC

A SUBSIDIARY OF TEXTRON INC.

35200 WEST RYE CANYON ROAD • VALENCIA, CALIFORNIA 91355
805 259-4030 • TWX 810-336 1438 • TELEX 69/1492DOCUMENT NO. HR77700072

PNEUMATIC SHUTDOWN DATA SHEET (ATP Para 4.11.3)

PN X41009110

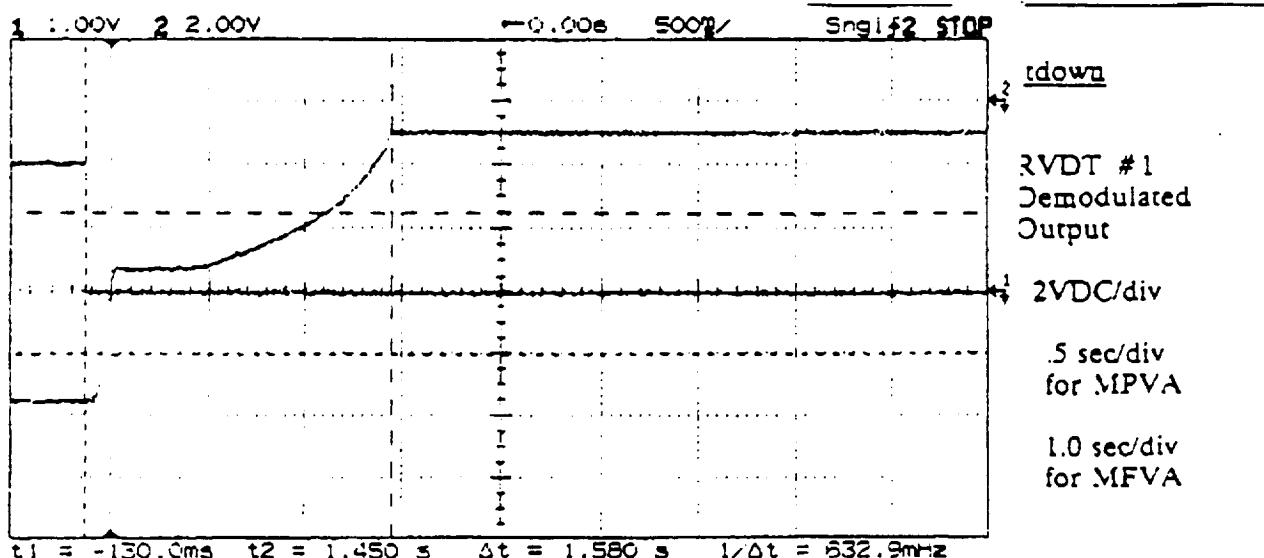
Date SEP 15 1992

Operator

Serial No. X001Comments: LOADED

Item	Required	Actual
Pneumatic Pressure, psig	695 ± 10	<u>695</u>
Starting Encoder, bits*	<u>MPVA</u> 2185 to 2196	<u>2171</u>
Ending Encoder, bits*	<u>MPVA</u> 256 to 299	<u>253</u>
Shutdown Time, sec	1.17 to 2.27	<u>1.58</u>

* Cross out non-applicable line.



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DOCUMENT NO. HR77700072

P/N X41009110 FAIL-OPERATE PERFORMANCE (ATP Para 4.11)

Date SEP 15 1992

Operator

Serial No. X001Comments: Loaded

Item	Required	Actual
#1 Input	+24 M amp	+24
#2 Input	-24 M amp	-24
Fail-Op Energized	20 M amp	20
Failsafe Energized	20 M amp	20
Ending Encoder Reading		777
Starting Encoder Reading		758
Diff. = Uncontrolled Actuator Travel	78 bits max.	19

Encoder Reading @ Travel Reversal: 777 BitsEncoder Reading @ Fail-Op Energized: 758 Bits Δ Position = Uncontrolled Actuator Travel: 19 Bits

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PAGE REVISION LETTER

FUTURE TEST PLANS

FUNCTIONAL

**FREQUENCY RESPONSE
RATED LOAD/VELOCITY
LINEARITY
STABILITY
PERFORMANCE**

ENVIRONMENTAL

**VIBRATION/SHOCK
EMI/EMC**

FLIGHT SIMULATION LABORATORY

**REDUNDANCY
FAULT INJECTIONS
ENGINE SIMULATIONS (HARDWARE IN-THE-LOOP)**

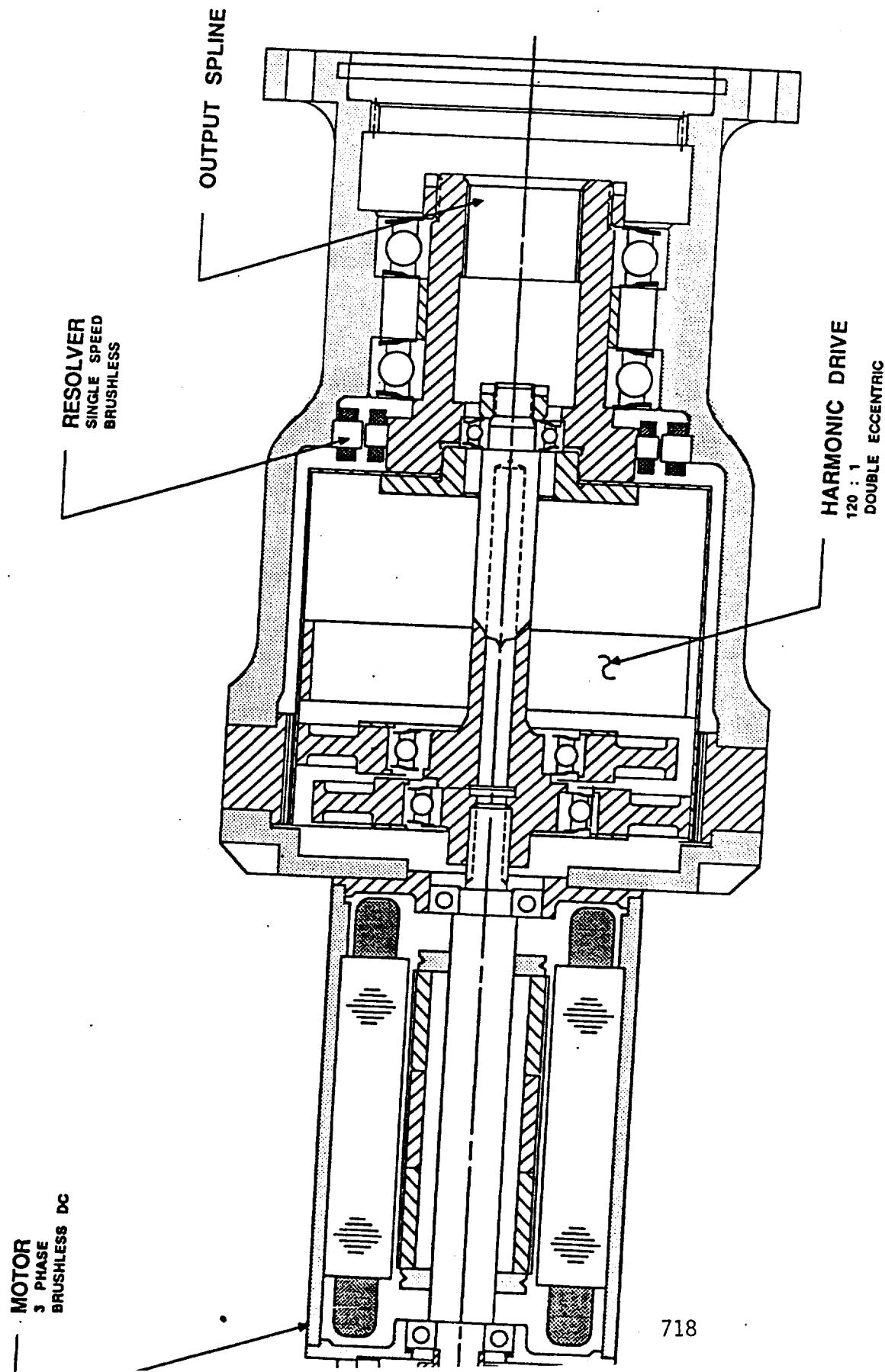
FLOW

WATER FLOW/CRYOGENICS WITH MOV

TTB

ENGINE HOT FIRE

SSME ELECTROMECHANICAL VALVE ACTUATOR



EMA DESIGN GROUPS

MECHANICAL

ELECTRONIC CONTROLLER

Propulsion Laboratory
Control Mechanisms &
Propellant Delivery Branch
(EP64)

Information & Electronics
Systems Laboratory
Control Electronics Branch
(EB24)

ELECTROMECHANICAL PROPELLANT CONTROL SYSTEM ACTUATOR

- DESIGN
 - MECHANICAL
 - ELECTRONICS/CONTROLLER
- TESTING
 - STATUS
- FUTURE PLANS

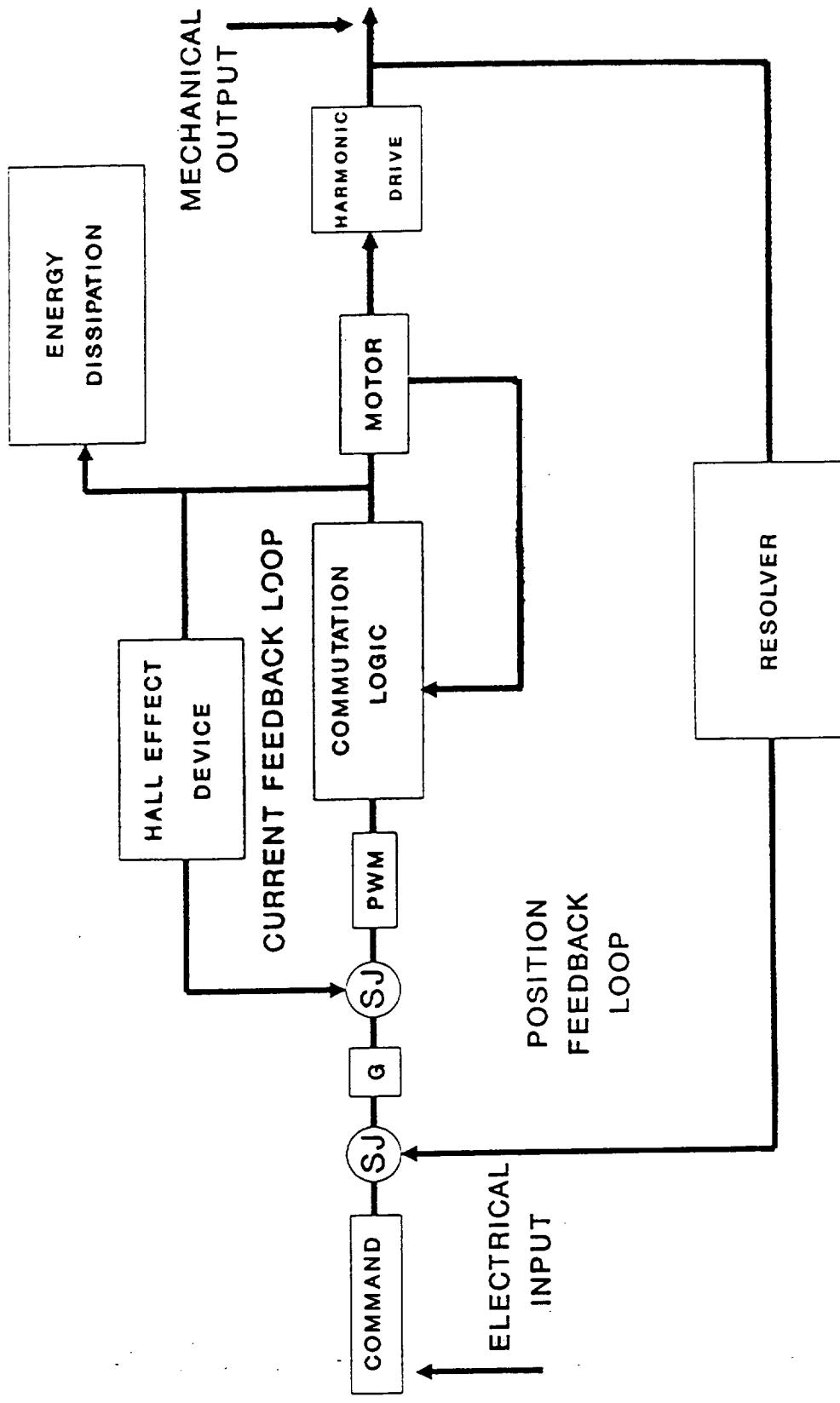
MECHANICAL COMPONENTS

- Motor
- Harmonic Drive
- Resolver
- Output Spline

ELECTRONIC CONTROLLER

- PROVIDES CONTROL TO MOTOR
- PROVIDES EXCITATION TO RESOLVER
- CONTAINS ENERGY DISSIPATING DEVICE

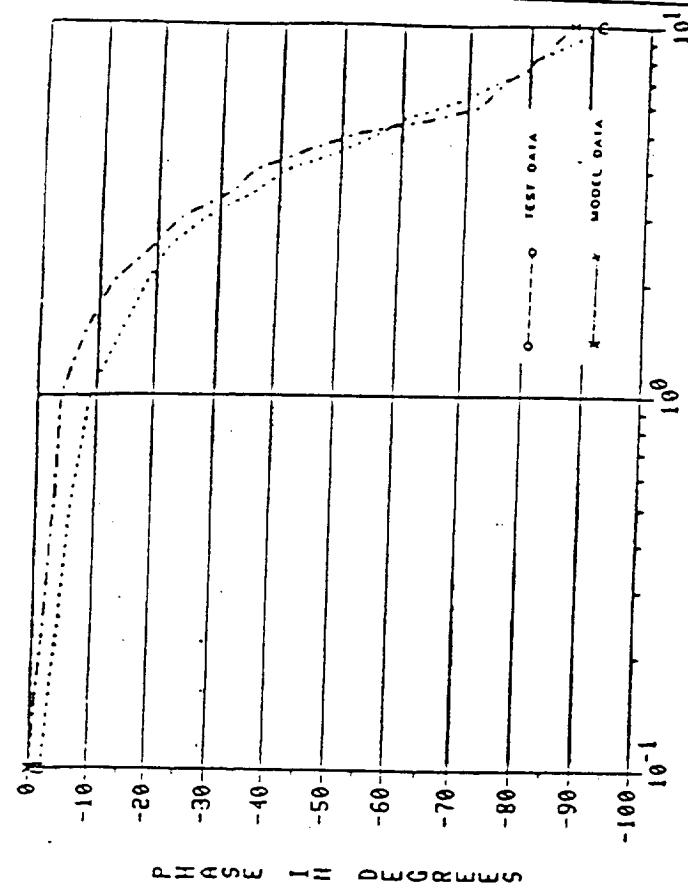
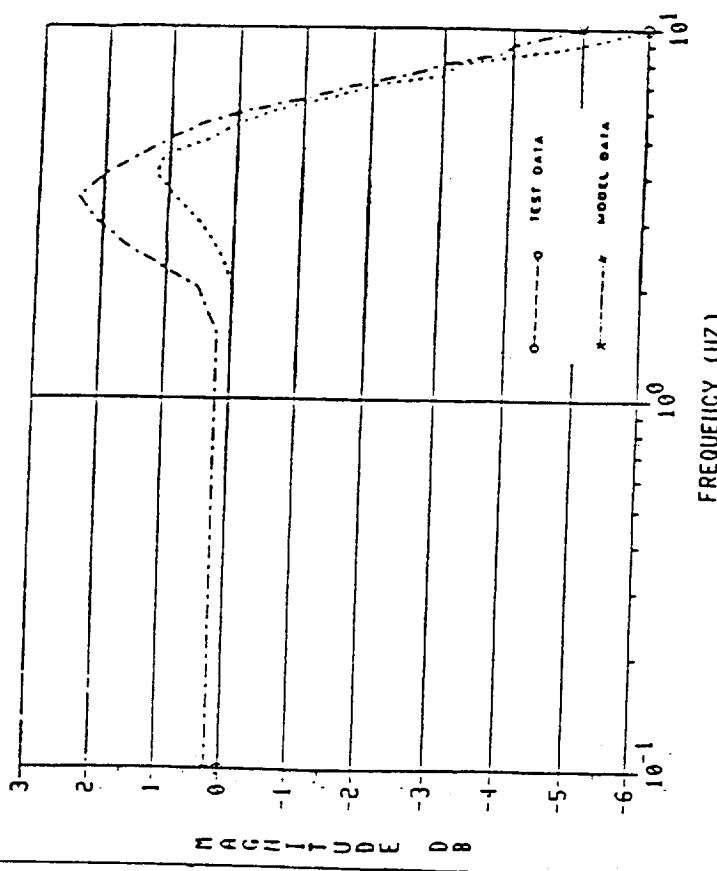
CONTROLLER BLOCK DIAGRAM



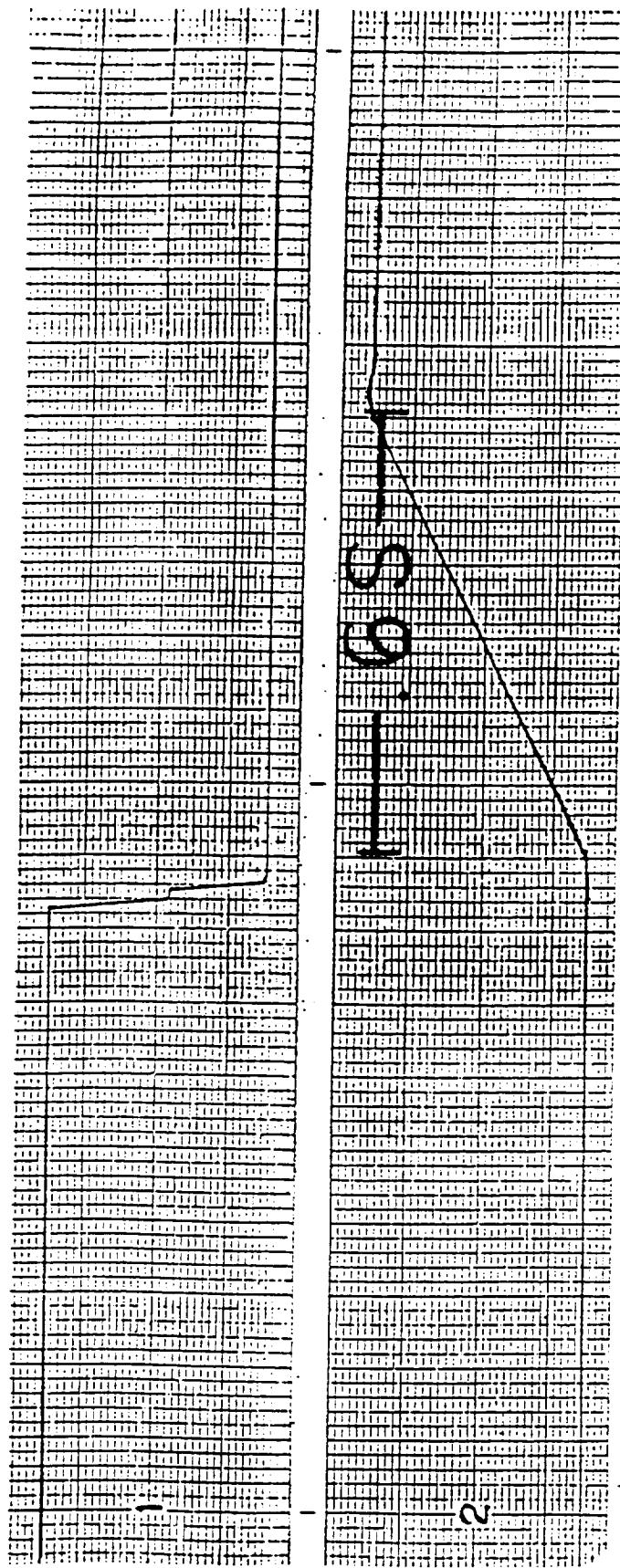
TESTING

- Developed and Verified Model
- Unloaded Testing
 - Frequency Response
 - Velocity
- Loaded Testing
 - Frequency Response

MODEL AND EMA FREQUENCY RESPONSE TESTS



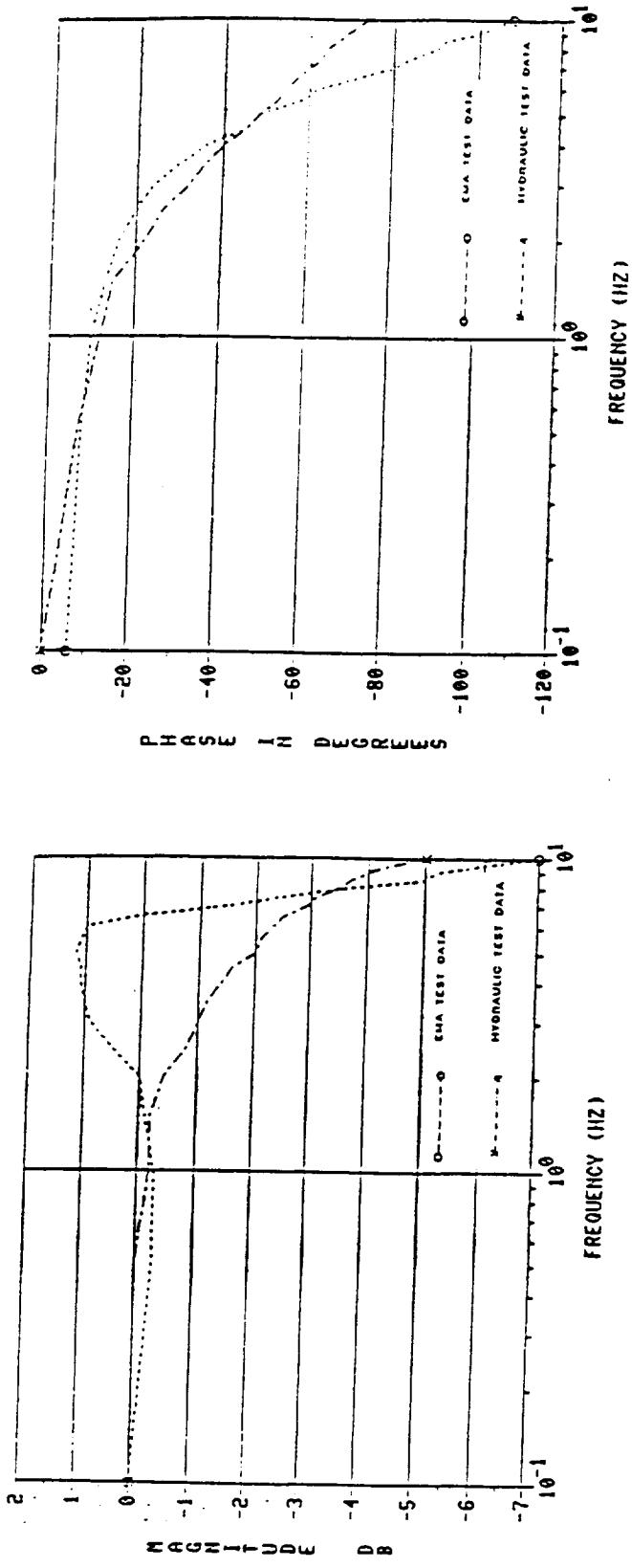
EMA NO-LOAD VELOCITY TEST



EQUIPMENT NEEDED TO
COMPLETE TESTING

- 4000 Watt Controller
- Valve Simulator

HYDRAULIC AND EMA FREQUENCY RESPONSE TESTS



FUTURE TEST PLANS

- Steady State Position Accuracy
- Temperature Tests
- Vibration Tests
- Comparison Between EMA And Hydraulic

TRANSIENT COMPENSATION EMA

Bill Fellows

September 29, 1992

Allied-Signal Aerospace Company

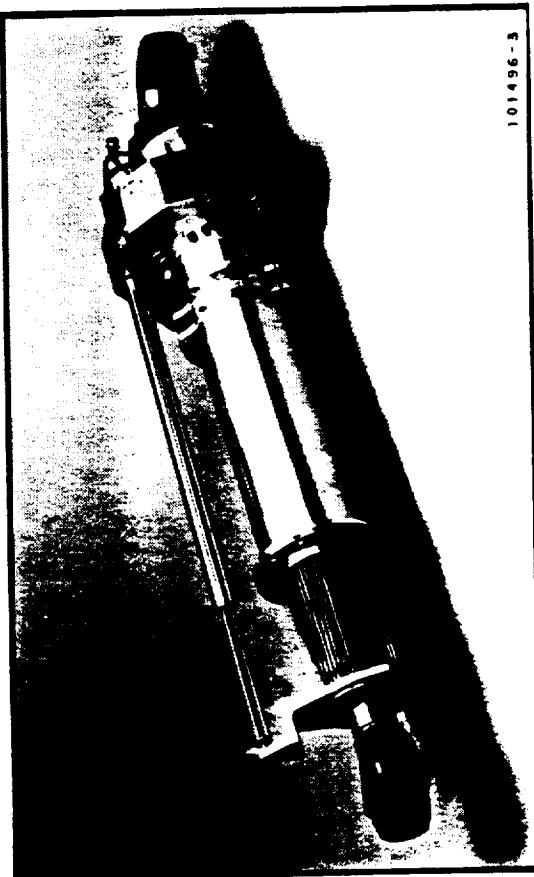
AiResearch Los Angeles Division



ALLIED-SIGNAL RESEARCH ELECTROMECHANICAL ACTUATOR (EMA)

SPECIFICATIONS

TRIPLE 11HP MOTORS
POWER: 270 VDC
FORCE: 35,000 LB
TRAVEL: 10 INCHES
TRAVEL TIME: 2 SEC'S
BANDWIDTH: 13 HZ
WEIGHT: 102 LB
LENGTH: 46 INCHES
(EXTENDED)



FEATURES

- REPLACES HYDRAULIC ACTUATORS
- FAULT TOLERANT ELECTRONICS
- BUILT-IN TEST CAPABILITY
- RATE AND POSITION COMMANDS
- FORM AND FIT COMPATIBLE WITH HYDRAULIC ACTUATORS
- HIGH EFFICIENCY

M-00280

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AiResearch Los Angeles Division

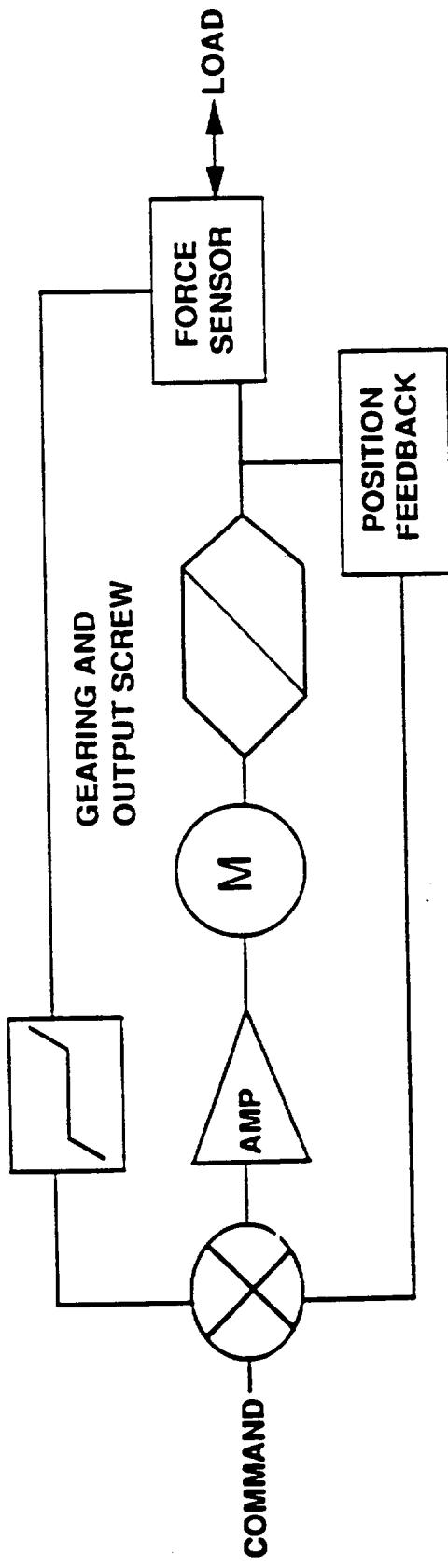


SYSTEM DESCRIPTION

FOR THE PURPOSE OF MODELING, A SYSTEM COMPRISED OF TWO ALLIED-SIGNAL F20 MOTORS WAS UTILIZED. THIS SYSTEM WILL MEET THE PERFORMANCE REQUIREMENTS OF THE TITAN IV FIRST STAGE. THE BLOCK DIAGRAM FOR THE SYSTEM IS SHOWN. THE REDUNDANCY ASPECTS OF HAVING TWO MOTORS IS NOT SHOWN - THE MOTORS ARE LUMPED INTO ONE FOR THIS STUDY. THE GEAR RATIO IS APPROXIMATELY 37:1 INTO A 0.625 LEAD BALLSCREW, FOR AN OVERALL GEAR RATIO OF 5400:1. THIS PROVIDES A 30,000 LB. OUTPUT OF THE ACTUATOR AT 3.5 IN-SEC. THE LIMIT LOAD OR STRUCTURAL CAPACITY OF THE ACTUATOR IS ASSUMED TO BE 60,000 LBS. MINIMUM, WHICH IS AT LEAST TWICE THE RATED OUTPUT. THE FORCE FEEDBACK INTO THE CONTROLLER HAS AN ELECTRICAL BIAS OF 40,000 LBS.

EM TVC TRANSIENT LOAD COMPENSATION

- IF THE REACTED FORCE ON THE ACTUATOR IS INSTRUMENTED, IT MAY BE FED BACK TO THE SERVO LOOP TO CAUSE A REDUCTION IN STIFFNESS WHEN THE LOAD TRIES TO EXCEED THE RATED LOAD

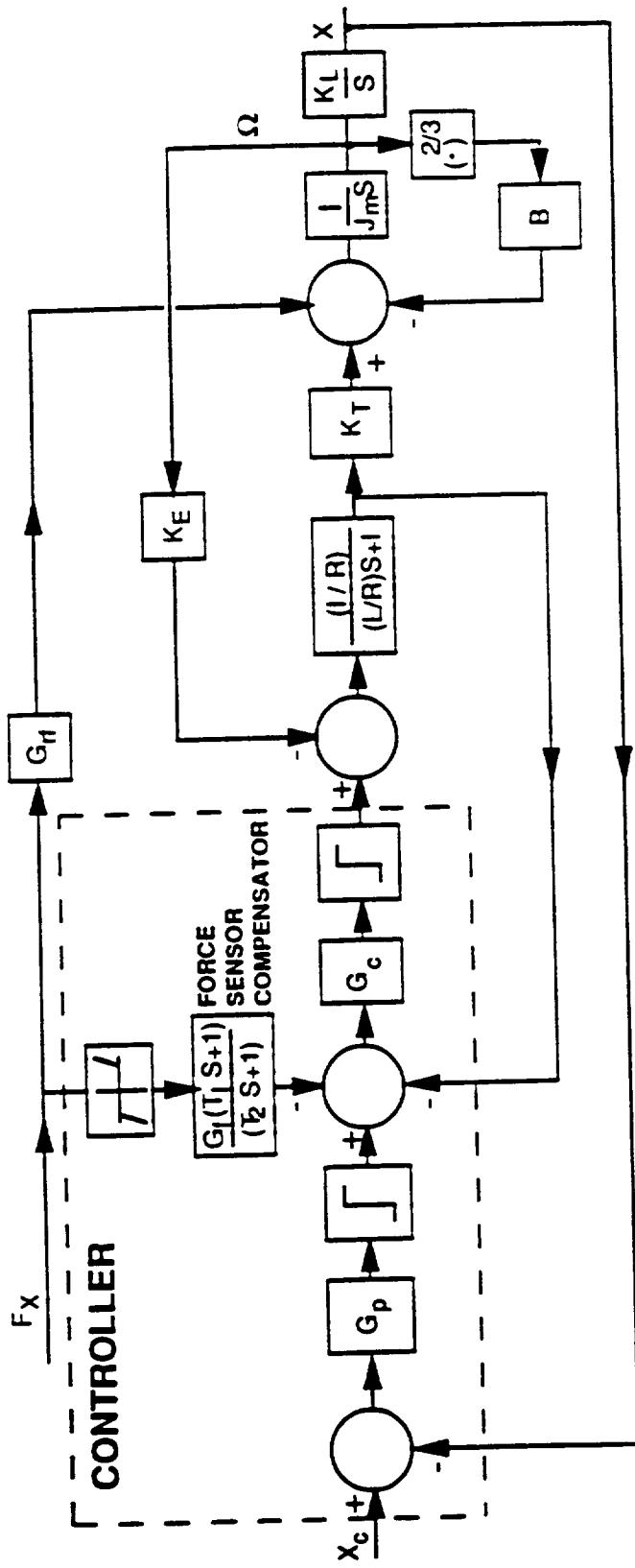


GENERAL DESCRIPTION OF ACTIVE COMPENSATION

THE BASIC PHILOSOPHY OF THE COMPENSATION IS TO DETECT THE APPLIED LOAD AND WHEN IT IS GOING TO EXCEED THE MAXIMUM ACTUATOR REQUIRED OUTPUT USE THIS LOAD TERM TO CAUSE THE ACTUATOR TO BACK AWAY FROM THE EXCESS TRANSIENT. THE RESPONSE OF THE TVC SYSTEM WHILE OPERATING UNDER NORMAL LOADS DOES NOT HAVE TO BE AS HIGH AS THE TRANSIENT LOAD. IN NORMAL OPERATION, THE ENGINE INERTIA AND LOADS HAVE A SIGNIFICANT EFFECT ON THE ACTUATOR RESPONSE CAPABILITIES. WHEN REACTING TO A TRANSIENT LOAD, THE ENGINE INERTIA IS THE MOVER AND THE RESPONSE CAPABILITY OF THE ACTUATOR TO MOVE OUT OF THE WAY IS THE RESPONSE OF THE ACTUATOR MOTOR ALONE, I.E., THE MOTOR MUST ACCELERATE WITH THE HELP OF AN AIDING LOAD. THIS MEANS THAT A SYSTEM WITH AN OPERATIONAL FREQUENCY RESPONSE OF 4 Hz MAY HAVE NO PROBLEM COMPENSATING FOR A 15 Hz TRANSIENT LOAD.

AS AN EXAMPLE OF THE ABOVE, A PRELIMINARY SIZING INDICATES THAT A TVC ACTUATOR USING TWO ALLIED-SIGNAL F20 BRUSHLESS DC MOTORS WILL MEET THE PERFORMANCE REQUIREMENTS OF TITAN IV. WHEN IN NORMAL OPERATION AND MOVING THE TITAN IV ENGINE, THE FREQUENCY RESPONSE IS IN THE ORDER OF 7 OR 8 Hz. THE RESPONSE CAPABILITY WHEN REACTING TO A TRANSIENT LOAD IS IN THE ORDER OF 19 Hz. THIS IS COMPATIBLE WITH REQUIREMENTS FOR COMPENSATING A 12 Hz TRANSIENT INPUT.

EM TRANSIENT LOAD COMPENSATION MODEL

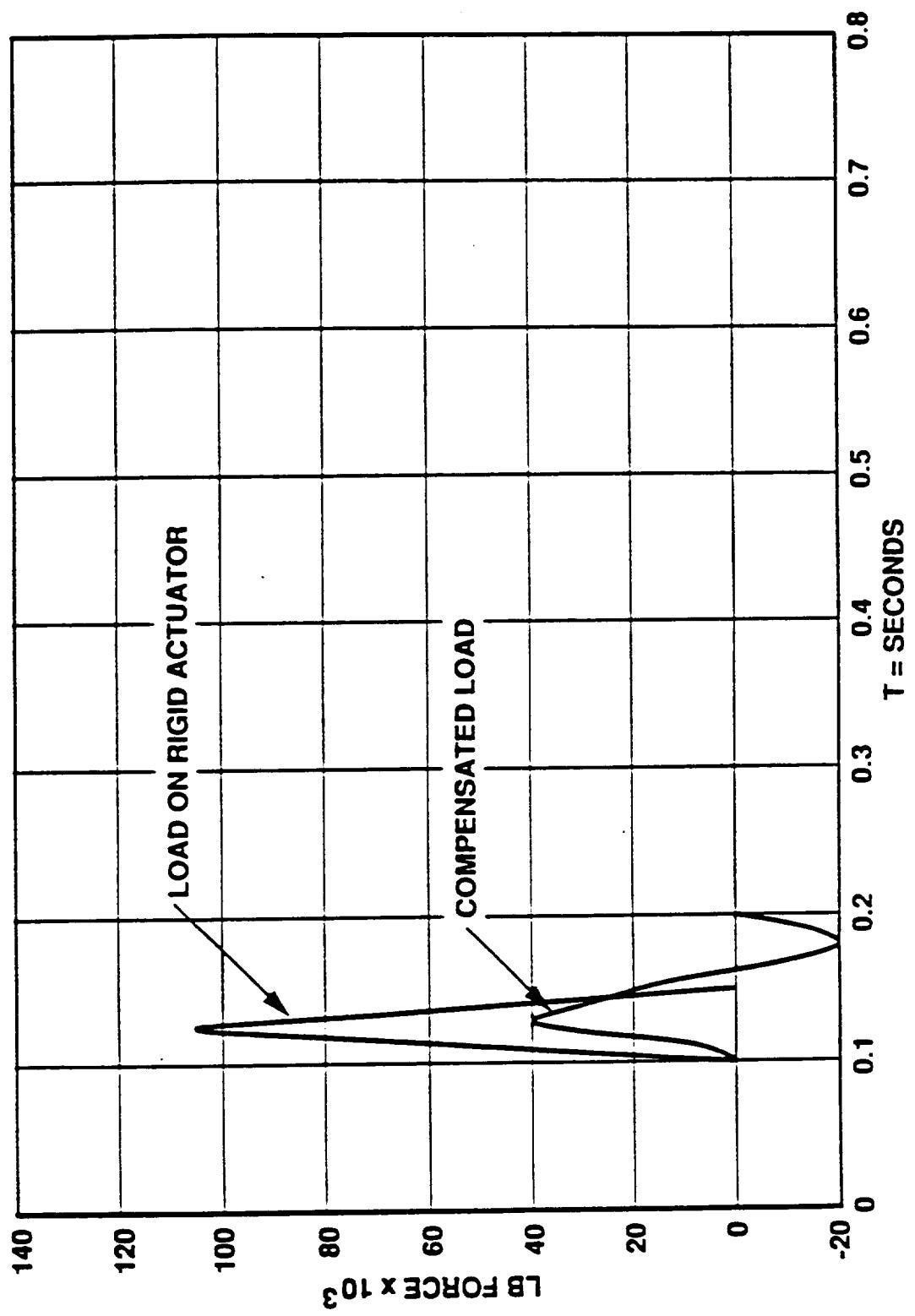


NOMENCLATURE

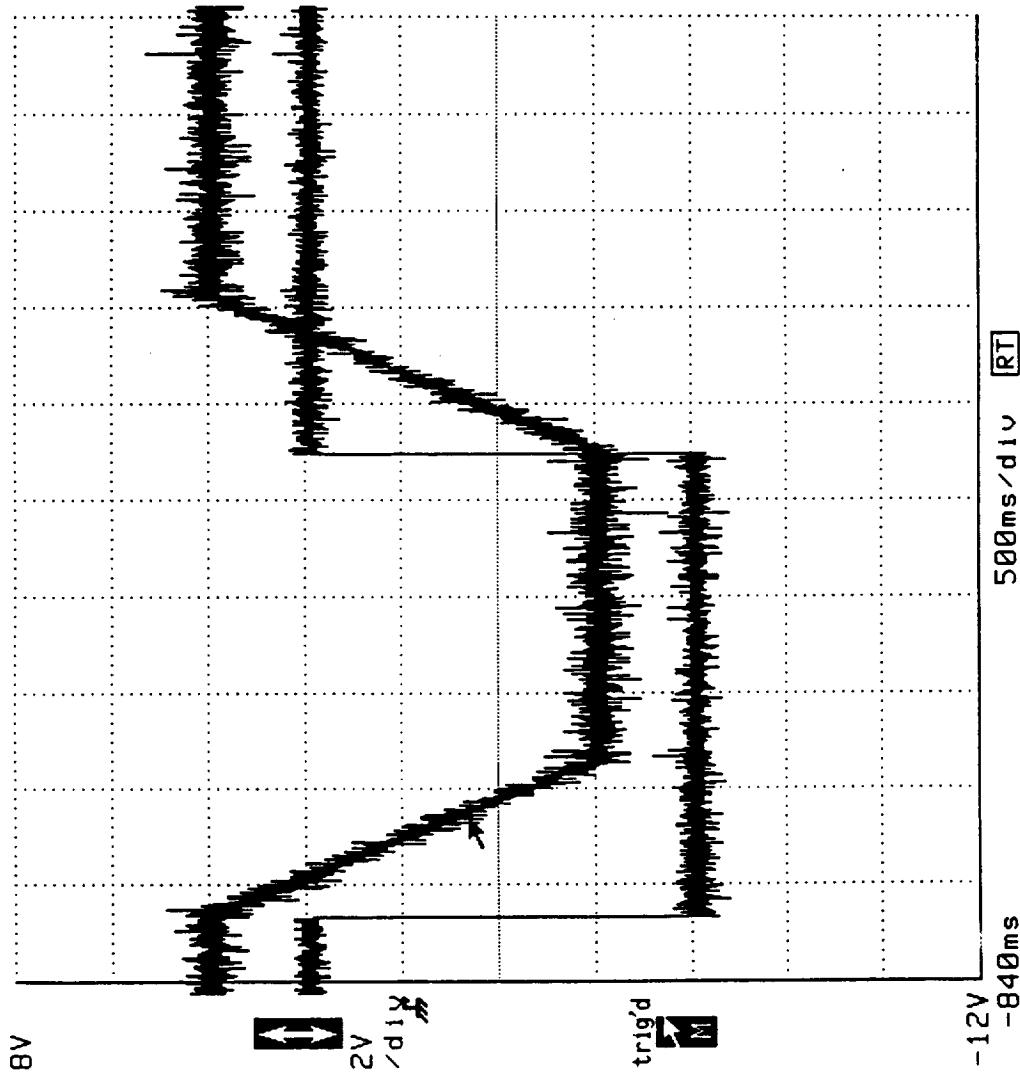
F_x	LOAD	J_m	MOTOR POLAR MOMENT OF INERTIA
X_c	POSITION COMMAND	K_L	COMBINED GEAR RATIO
X	ACTUAL POSITION	K_T	TORQUE CONSTANT
K_E	BACK EMF CONSTANT	I_m	MOTOR CURRENT
Ω	MOTOR SPEED	G_p, G_c, G_i	GAIN CONSTANTS
R	RESISTANCE	T_1, T_2	LEAD COMPENSATOR TIME CONSTANTS
L	INDUCTANCE		

MODEL AND RESULTS

USING THE SYSTEM DESCRIBED, A 12 HZ TRANSIENT WAS APPLIED WHICH HAD A PEAK UNCOMPENSATED FORCE OF 105,000 LBS. THIS LEVEL WAS SELECTED HIGH BECAUSE COMPLETE DATA ON THE TRANSIENT CHARACTERISTICS ARE NOT AVAILABLE. FOR COMPARISON, TWO ENERGY LEVELS OF TRANSIENTS WERE USED: A 1500 IN-LB. AND A 7500 IN-LB. THE CONTROLLER IN THE MODEL HAS A 40,000 LB. DEADBAND WHICH IS 10,000 LBS. OVER THE RATED OUTPUT. THIS MEANS THAT UNDER STATIC CONDITIONS, THE ACTUATOR WILL BE RIGID FOR ANY LOADS UNDER 40,000 LBS. THE REACTION AND RESULTS OF THE MODELED SYSTEM TO THE 1500 IN-LB. LEVEL IS SHOWN. THE ABILITY OF THE SYSTEM TO REDUCE THE LOAD AT THE 7500 IN-LB. LEVEL IS LIMITED BY THE SPEED LIMITATION OF THE ACTUATOR, NOT ITS FREQUENCY RESPONSE. IN OTHER WORDS, IT CANNOT MOVE ENOUGH DISTANCE IN THE TIME TO FURTHER REDUCE THE TRANSIENT. EVEN WITH THIS LIMITATION, THE LOAD WAS REDUCED FROM ABOUT 105,000 LBS. TO 55,000 LBS., WELL WITHIN THE STRUCTURAL LIMIT REQUIREMENTS. AT THE 1500 IN-LB. ENERGY LEVEL, THE FORCE WAS REDUCED TO 40,000 LBS. IN EITHER CASE, IT CAN BE SEEN THAT THE COMPENSATION SIGNIFICANTLY REDUCES THE PEAK LOAD TO WITHIN STRUCTURAL LIMITATIONS WHICH IS TAKEN TO BE 60,000 LBS.



NO LOAD STEP RESPONSE

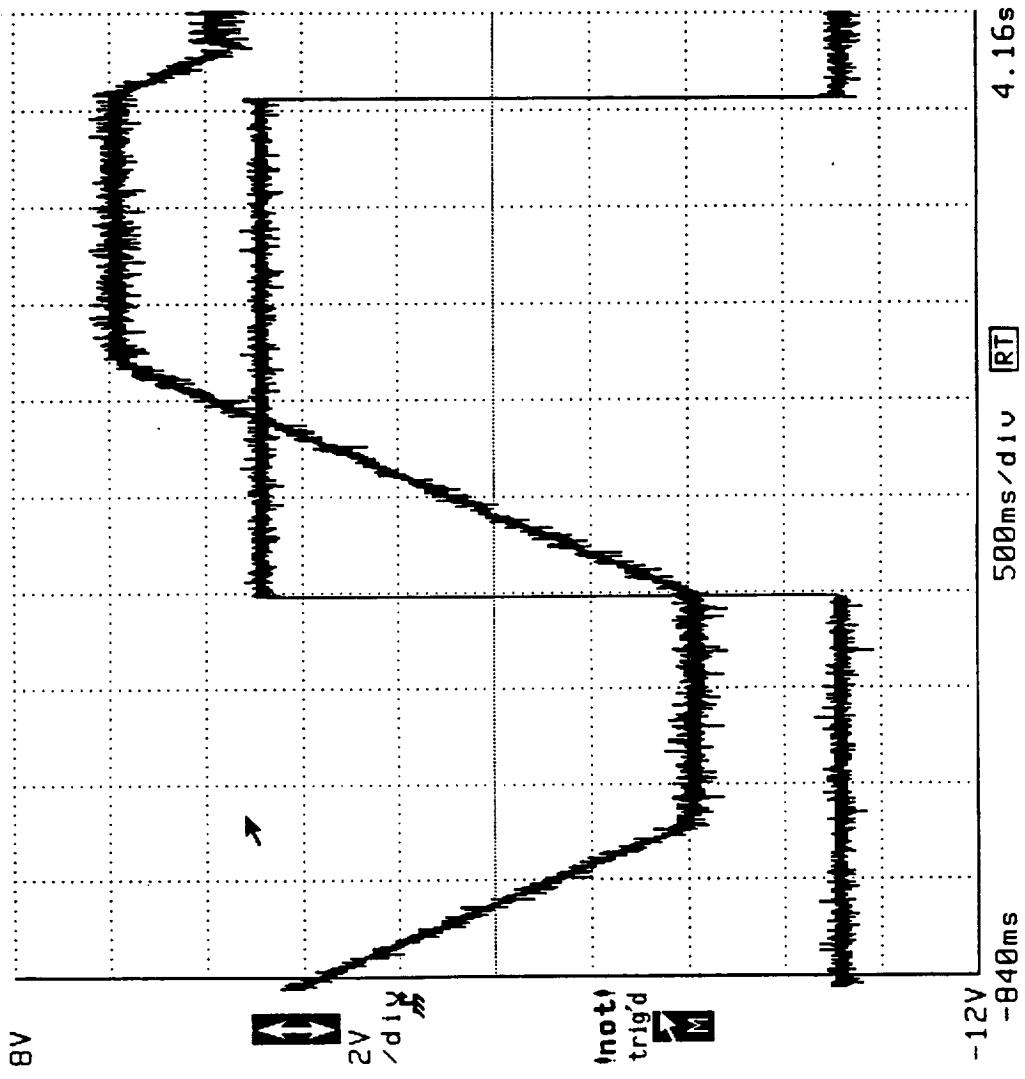


Allied-Signal Aerospace Company
AirResearch Los Angeles Division



MASS LOADED STEP RESPONSE

6600 POUNDS



Allied-Signal Aerospace Company

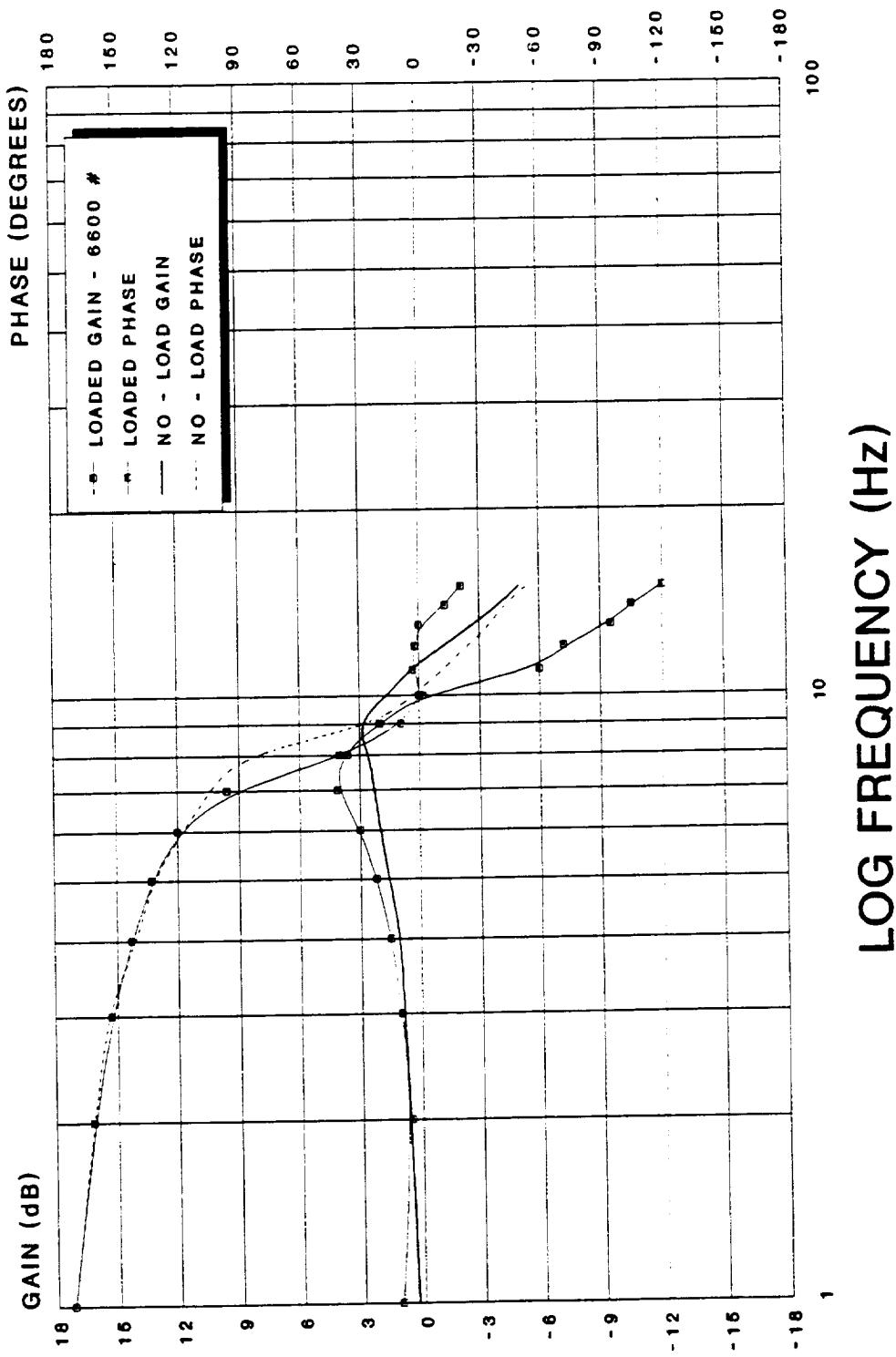
AiResearch Los Angeles Division



FREQUENCY RESPONSE

THE FREQUENCY RESPONSE OF THE TEST UNIT WAS RUN BOTH UNLOADED AND WITH A 6600 LB. INERTIA LOAD. THE RESULTS SHOW THAT THE RESPONSE EXCEEDS 10 Hz IN BOTH CASES.

GAIN AND PHASE 6600 POUND LOAD AND NO - LOAD



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